Chapter 7—Aerial Structures/Bridges

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CHAPTER 7—AERIAL STRUCTURES/BRIDGES

7.1 INTRODUCTION

Railway aerial structures started as ballasted track structures that had little structural interaction between the rails and the structure. Urban railways and long span lift bridges have been constructed with open deck designs. These lighter structures used jointed rail to limit the interaction between the rail and the structure. CWR direct fixation track on a concrete deck is typical of modern light rail aerial structures. These structures can have significant interaction between the rail, which does not move, and the structure, which must expand and contract with changes in temperature. This chapter discusses the resolution of rail/structure interaction issues and presents the items to be considered during the design of aerial structures.

The design of aerial structures for light rail transit systems involves choosing a design code, determining light rail vehicle (LRV) forces, confirming track configuration requirements, and applying rail/structure interaction forces. This interaction is affected by such factors as the bearing arrangement at the substructure units, trackwork terminating on the aerial structure, type of deck construction, and type of rail fasteners.

The structural engineer must coordinate with the trackwork engineer to fully understand the issues that affect the design of an aerial structure. The details of the trackwork design significantly affect the magnitude of the forces that must be resisted by the aerial structure.

7.2 DESIGN CODES

At present there is no nationally accepted design code that has been developed specifically for light rail transit aerial structures. In addition to local design codes, designers must choose between the *Standard Specifications for Highway Bridges,* published by the American Association of State Highway and Transportation Officials (AASHTO) and the *Manual for Railway Engineering* issued by the American Railway Engineering and Maintenance of Way Association (AREMA). Unfortunately, neither the AASHTO nor AREMA code accurately defines the requirements of an aerial structure to resist light rail transit loads, although the AASHTO code is probably more applicable.

Most light rail loads are greater than the HS20 truck load used by AASHTO, but they are much less than the Cooper E80 railroad loading cited in the AREMA code. **Figure 7.2.1** plots bending moment versus span length for the Cooper E80 train load, the HS20 truck load, and the LRV load from the Dallas and St. Louis transit systems. As shown in the figure, for a 30.5-meter (100-foot) span, the LRV produces a bending moment approximately 50 percent higher than that produced by the HS20 truck load, but less than 20 percent of the bending moment caused by the Cooper E80 train load.

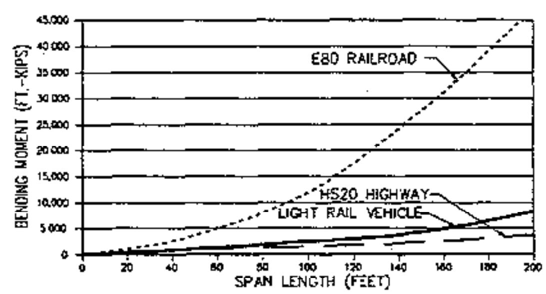


Figure 7.2.1 Vehicle Bending Moments on Simple Spans [1]

The AREMA code, although applicable to railroad structures, is too restrictive for light rail transit structures due to the great difference in loadings. Wheel spacings for

AREMA loading do not correspond to those found on LRVs, and the AREMA impact criterion is not consistent with the suspension and drive systems used on LRVs. The service conditions, frequencies, and types of loading applicable to freight railroad bridges are not consistent with those items on dedicated light rail transit systems. [1, 2]

Alternately, a strong similarity exists between light rail transit design requirements and the AASHTO code. For light rail transit aerial structures, the ratio of live load to dead load more closely approximates that of highway loadings than freight railroad loadings. In addition, since the magnitude of the transit live load can be more accurately predicted, the conservatism inherent in the AREMA code is not required in light rail transit structures.

It is interesting to note that the older transit systems (Chicago, Philadelphia, New York) often refer to the AREMA code for design of their bridges, but the newer systems (Atlanta, Washington, Baltimore) base their designs on AASHTO specifications. This is partly due to an increased understanding of an aerial structure's behavior and the designer's confidence in the ability to more accurately predict the transit loads. Both heavy rail and light rail transit systems can use AASHTO as a guide since their axle loads and car weights are similar.

Although there is no current bridge design code that is completely applicable to light rail transit bridges, the use of the AASHTO code will result in a conservative design that is not overly restrictive or uneconomical. [1,2,3]

7.3 VEHICLE FORCES

The vehicle forces applied to an aerial structure are often set by the transit agency's design criteria for site-specific circumstances. Many transit properties include alternative heavier vehicles in the design criteria for aerial structures These alternative maintenance/construction vehicles include a crane car, maintenance car, work train with locomotive, and even highway vehicles (during construction). On the other hand, some transit properties establish the LRV as the basis of design for the aerial structures.

In addition to the LRV and alternative vehicle live loads applied to the aerial structure, the following vehicle forces are considered:

- Vertical impact
- Transverse horizontal impact
- Centrifugal force
- Rolling force (vertical force applied at each rail, one up and one down)
- Longitudinal force from braking and tractive effort
- Derailment force

Combinations of vehicle forces, in conjunction with dead loads, wind loads, and seismic loads, are developed to generate the load cases that govern the design of an aerial structure.

7.4 TRACK CONFIGURATION

The majority of the early transit systems used trackwork comprised of jointed rail supported on elevated, simple-span guideway structures. Alternatives have been developed for light rail transit trackwork. Rather than the classical jointed rail with bolted connections every 12 meters (39 feet), the trackwork is normally constructed with continuous welded rail. With either rail configuration, the rails can be fastened directly to the aerial structure's deck or installed on ties and ballast.

The bolted connections used with jointed rail allow sufficient longitudinal expansion and contraction to reduce the accumulation of thermal stresses along the rails. But bolted joints have the following disadvantages:[4]

- Generate noise and vibration
- Are troublesome to maintain
- Contribute to derailments
- Cause rail fatigue in the proximity of the rail joints
- Cause wear of the rolling stock
- Reduce ride quality
- Increase the dynamic impact forces applied to the aerial structure

Over the past 20 years, CWR has been the most common track configuration for light rail transit systems. This is mainly due to its ability to overcome many of the disadvantages of jointed rail. Specifically, CWR:[5, 6]

- Minimizes noise and vibration
- Reduces track maintenance
- Improves track safety
- Eliminates the joints that cause rail fatigue
- Limits wear of the rolling stock
- Provides a smooth, quiet ride
- Limits the dynamic impact forces applied to the aerial structure

The use of CWR, combined with direct fixation of the rails to the supporting structure, is an improvement in the support and geometric stability of the trackwork. As a result, rider comfort and safety is enhanced and track maintenance requirements are decreased.

The use of CWR requires designers of trackwork and aerial structures to consider items that are neglected with the use of jointed rail, such as:[7, 8, 9]

- Providing sufficient rail restraint to prevent horizontal or vertical buckling of the rails
- Providing anchorage of the CWR to prevent excessive rail gaps from forming if the rail breaks at low temperature
- Determining the effect a rail break could have on an aerial structure
- Calculating the thermal forces applied to the aerial structure, the rail, and the fasteners as the aerial structure expands and contracts, while the CWR remains in a fixed position
- Providing a connection between the CWR and aerial structure (direct fixation fasteners) that is resilient enough to permit the structure to expand and contract without overstressing the fasteners

An important element in the design of trackwork using CWR is the consideration of rail breaks. Rail breaks often occur at structural expansion joints in the aerial structure and must be accommodated without catastrophic effects such as derailment of the vehicle. Depending on the length of the aerial structure, the CWR has to be sufficiently restrained on the aerial structure to limit the length of the gap if the rail does break.

CWR is a standard now employed in the transit industry. Therefore, transit system designers must understand how it interacts with aerial structures as the temperature changes in order to provide a safe track and structure.

Expansion (sliding) rail joints are used in certain circumstances to reduce the interactive forces between the CWR and the structure. These include locations where special trackwork is installed on the aerial structure, where signal track circuits need to be accommodated, and where the aerial structure includes very long spans.

Rails can be attached to the structure in a variety of ways. The most common mechanism is the use of direct fixation fasteners with spring clips. Rigid rail clips have also been used in the vicinity of substructure units (piers and abutments) with fixed bearings, as well as adjacent to special trackwork. Also, zero longitudinal restraint fasteners have been installed to minimize the interaction forces between CWR and an existing aerial structure.

7.5 RAIL/STRUCTURE INTERACTION

7.5.1 General

With widespread use of CWR, the designer of an aerial structure must be aware of trackwork design and installation procedures, as well as vehicle performance and ride comfort issues. Trackwork design and installation procedures are especially critical in establishing the magnitude of the interaction forces between the rail and aerial structure.

As the temperature changes, the superstructure (deck and girders) expands or contracts. The rails are basically stationary because of their continuity throughout the length of the bridge and because they are anchored off the bridge. The movement of the superstructure as the temperature changes imposes deformation on the fastening system that attaches the rails to the bridge deck.

This thermal action exerts additional interactive axial forces and deformations on the rails and superstructure. Reaction loads are applied to the substructure (piers and abutments) through the fixed bearings and by shear or friction through the expansion bearings. The aerial structure must also resist lateral components of the longitudinal loads on curved track. When the cumulative resistance of the fastening devices (rail clips) along a length of superstructure is overcome, the superstructure slides relative to the rail.

Since CWR is not able to expand or contract, temperature increases above the rail installation temperature cause compressive forces that could buckle the rail. Rail fasteners prevent buckling of the rail. Temperature decreases below the rail installation temperature cause tensile forces that increase the probability of a rail break (pull-apart). A rail break creates unbalanced forces and moments in the aerial structure and results in a gap in the rail that could cause a derailment. Rail breaks are discussed in further detail in Section 7.5.4.

Based on these thermal effects, there are three problems to address in the design of aerial structures with CWR:

1. Controlling the stresses in the rail attributed to the differential longitudinal motions between the rail and the superstructure because of temperature changes or other causes
2. Controlling the rail break gap size and resulting loads into the superstructure
3. Transferring of superstructure loads and moments into the substructure

A structural system is formed when CWR track is installed on an aerial structure. The major components of this system include:[6]

- Long, elastic CWR, whose ends are anchored in ballasted track beyond the abutments
- Elastic rail fasteners that attach the rails directly to the superstructure
- The elastic superstructure
- Elastic bearings connecting the girders to the substructure
- The elastic substructure anchored to rigid foundations

There are a number of principal design factors that affect the magnitude of the interaction movement and forces between the rails and the structure, including:[10, 11]

- The composition of the girder material (steel or concrete) will affect the expansion/contraction response to temperature changes

- The girder length and type (simple span or continuous) will affect the magnitude of the structure's thermal movement that the rail fasteners must accommodate
- The girder's support pattern of fixed and expansion bearings from adjacent spans on the piers (refer to Section 7.5.2)
- The magnitude of the temperature change
- The rail fastener layout and longitudinal restraint characteristics; there are at least four concepts of fastener and restraint
  1. Frictional restraint developed in mechanical fasteners
  2. Elastic restraint developed in elastic fasteners
  3. Elastic restraint developed in elastic fasteners with controlled rail slip
  4. Elastic and slip fasteners installed in accordance with the expected relative movements between girder and rail; install sufficient elastic fasteners near the fixed bearing to control rail creep; install slip fasteners over the balance of the girder length to provide full lateral restraint and minimal longitudinal restraint

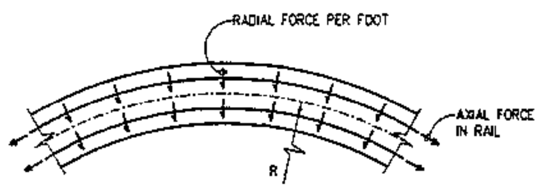
Depending on the method used to attach the rails to the structure, the structural engineer must design the structure for longitudinal restraint loads induced by the fasteners, horizontal forces due to a rail break, and radial forces caused by thermal changes in rails on curved alignments. Today's designer can use computer models to simulate the entire structure/trackwork system to account for variations in the stiffness of the substructure and the dissipation of rail/structure interaction forces due to the substructure's deflection (see Section 7.5.3).

The thermal force in the rail is calculated by the following equation: [4, 7, 8]

$$F_r = A_r E_r \alpha (T_i - T_o) \qquad \text{(Eqn 1)}$$

where: F_r = thermal rail force
A_r = cross sectional area of the rail
E_r = modulus of elasticity of steel
α = coefficient of thermal expansion
T_i = final rail temperature
T_o = effective construction temperature of the rail

On horizontal curves, the axial forces in the rail and superstructure result in radial forces. These radial forces are transferred to the substructure by the bearings. The magnitude of the radial force is a function of rail temperature, rail size, curve radius, and longitudinal fastener restraint. Refer to **Figure 7.5.1** as well as other pertinent publications for the equation to calculate the radial rail/structure interaction force.



$$\text{RADIAL FORCE PER FOOT PER RAIL} = \underbrace{\frac{E \alpha \Delta T A_R}{R}}_{\text{THERMAL COMPONENT}} + \underbrace{\frac{K_F \, l_{CONT}}{4}}_{\text{INTERACTION COMPONENT}}$$

WHERE: E = MODULUS OF ELASTICITY OF RAIL STEEL
α = COEFFICIENT OF THERMAL EXPANSION OF RAIL STEEL
ΔT = CHANGE IN RAIL TEMPERATURE FROM STRESS-FREE TEMPERATURE
A_R = AREA OF RAIL SECTION
R = RADIUS OF HORIZONTAL CURVE
K_F = FASTENER SLIP VALUE DIVIDED BY FASTENER SPACING
l_{CONT} = LENGTH OF STRUCTURE BETWEEN EXPANSION JOINTS

Figure 7.5.1 Radial Rail/Structure Interaction Forces [17]

Various solutions have been implemented in an attempt to minimize the interaction forces caused by placing CWR on aerial structures, including the use of:

- Ballasted track instead of direct fixation track (refer to Section 7.5.6)
- Zero longitudinal restraint fasteners (refer to Section 7.6)
- High-restraint fasteners near the structure's point of fixity and low-restraint fasteners on the remainder of the

structure (Note: it has been reported that this solution results in problems with rail creep and excessive rail gaps at breaks in the rail)

- A series of rail expansion joints and low-restraint fasteners to allow the rail to move independent of the structure; requires highly restrained zones to transfer traction and braking forces to the structure.

7.5.2 Bearing Arrangement at the Piers

The magnitude of rail/structure interaction forces transferred to the substructure depends heavily on the bearing arrangement used. As shown in **Figure 7.5.2**, there are three commonly used bearing arrangements. Configuration A is a symmetrical bearing arrangement, with fixed bearings (or expansion bearings) from adjacent spans at the same pier. Configurations A and B are commonly used on modern transit systems that utilize CWR. Configuration C is a non-symmetrical bearing arrangement typically used on railroad and highway bridges.

As a guideline for light rail transit systems with CWR, the symmetrical bearing arrangement is the most desirable. In this arrangement, the thermal interactive forces induced into the rail tend to cancel out each other. This is true as long as the adjacent spans are of similar length and geometry. On the contrary, if an expansion bearing at the end of one span is coupled with a fixed bearing at the end of the adjacent span on the shared pier (Configuration C), then the thermal interactive forces would have a cumulative effect.

Although the interactive forces at symmetrical bearing arrangements tend to cancel out before loading the piers, the structural engineer must still design the bearings and their anchor bolts to resist these forces.

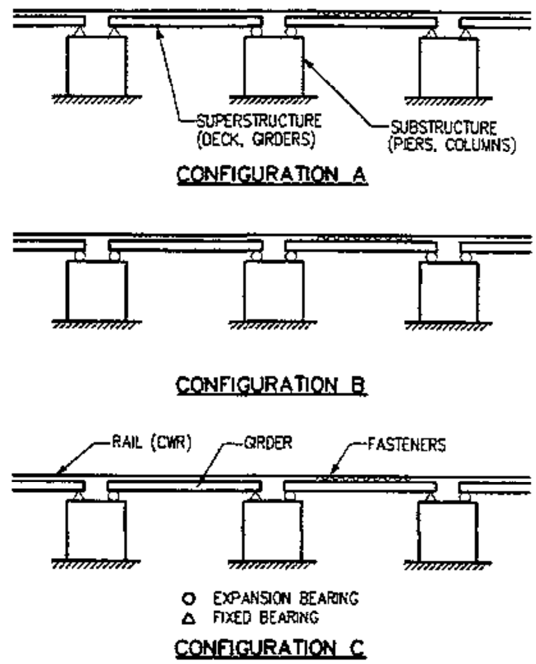


Figure 7.5.2 Bearing Configurations for Elevated Structure Girders [17]

7.5.3 Rail/Structure Interaction Analysis

Opinions differ throughout the transit design "community" regarding the level of complexity required to design aerial structures subjected to thermal interaction forces from CWR. The interaction of the rails and supporting structure involves the control of rail creep, broken rail gaps, stresses induced in the CWR, axial stresses induced in the guideway structure, and longitudinal and transverse forces developed in the supporting substructure.[8]

Some suggest that hand calculations are adequate and provide a good understanding of the important considerations of rail/structure interaction. Today's structural engineer has the advantage of being able to use computer software to more "exactly" analyze this complex interaction.

Others have found that simpler analysis methods are unreliable in predicting stresses and structural behavior critical to significant CWR-related design elements.[5] These design elements include:

- The control of stresses in rails attributed to thermally induced differential movements between the rail and supporting superstructure
- The control of the rail break gap size and the resulting loads transferred into structures during low-temperature rail pull-apart failures
- The transfer of thermally induced loads from the superstructure, through the bearings, into the substructure

The choice of the method used to analyze rail/structure interaction forces is clearly at the discretion of the experienced structural engineer. Depending on the length of the aerial structure and other considerations, simple formulas may be used to determine the structural requirements. Alternately, complexities such as curved alignments, varying span lengths, and the type of structural elements may require that a rigorous three-dimensional structural analysis be performed. At times, the transit agency's design criteria will include the required analysis methodology.

7.5.4 Rail Break/Rail Gap Occurrences

A rail break occurs when a thermally induced tensile force, resulting from a significant decrease in temperature, exceeds the ultimate tensile strength of the rail. The rail break is likely to occur at or near an expansion joint in the superstructure or at a bad weld, a rail flaw, or other weak spot in the rail.

The structure's expansion joint is a likely general area where a rail break can occur because the girder's end rotations increase flexural stresses in the rail and the tensile stress already in the rail is likely to be at its maximum value at this location.[4, 7, 12]

A broken rail on a light rail transit bridge is an important consideration because of the potential to transfer a large force to the bridge or for a derailment because of the formation of a rail gap. As a result, aerial structure designers must consider the rail break condition. Limits on the size of the rail gap have to be established, usually based on the light rail vehicle's wheel diameter. It is commonly assumed that only one rail of a single- or double-track alignment will break at any one time.

When the rail breaks, the pads of the fasteners situated between the break and the thermal neutral point are realigned in the opposite direction. Then, the rail slips through the fasteners whose pads have deformed beyond their elastic limit, engaging enough fasteners to resist the remaining thermal force. Once the required number of fasteners is engaged to balance the thermal force in the rail, the rail ceases to move.

The unbalanced force from the broken rail is resisted by the other unbroken rail(s) and the aerial structure. The portion of the rail break force that is resisted by the unbroken rail(s) versus the aerial structure is significantly affected by the substructure's longitudinal stiffness (the force required to induce a unit deformation in a component), the bearing configuration, and the rail fastener's restraint characteristics.[5]

Refer to **Table 7.1** for a comparison of the rail gap size for different column stiffnesses and levels of fastener restraint. Note that progressively lower loads are transferred to the columns as column stiffness decreases. As a result, higher loads are transferred to the unbroken rails. This increases the thermally induced stress in this rail and raises the possibility of a second rail break. With higher restraint fasteners, more load is transferred to the unbroken rail and less to the column than with medium-restraint fasteners.

Researchers found that the superstructure's bearing arrangement, as discussed in Section 7.5.2, has little effect on rail gap size. But decreasing the fastener's longitudinal stiffness or slip force limit, or both, will result in an increased rail gap size.

The redistribution of the rail break force to the substructure causes a longitudinal deflection in the substructure. The resulting substructure deflection, with the thermal slip of the broken rail, combine to create the total gap in the broken rail.

Several methods can be used to calculate the potential rail gap size. Following are the equations discussed herein:[5]

Rail gap size is generally estimated by the following equation:

$$G=2(X_{C1}+X_{C2}-X_{C3}) \quad \text{(Eqn. 2)}$$

where:

- G = rail gap, cm (in.)
- X_{C1} = P_{fns}/K_f, the maximum longitudinal deflection of the non-slip fastener
- X_{C2} = $\alpha \Delta T L_S$, the nominal rail contraction
- X_{C3} = $(n_S P_{fs} + n_{ns} P_{fns}) L_s / 2 A_r E_r$, the reduction in rail contraction caused by fastener constraint
- α = coefficient of expansion, 1.17×10^{-5} cm/cm/°C (6.5×10^{-6} in./in./°F) for steel
- ΔT = temperature change, °C (°F)
- L_s = length of span (fixed to expansion point), cm (in.)
- P_{fs} = minimum longitudinal restraint force in controlled slip fastener kg (lb.)
- P_{fns} = minimum longitudinal restraint force in non-slip fastener, kg (lb.)
- K_f = fastener longitudinal stiffness kg/cm (lb./in.)
- n_{ns} = number of non-slip fasteners in span
- n_s = number of controlled-slip fasteners in span
- A_r = cross-sectional area of rail (72.58 cm^2 [11.25 $in.^2$] for 115 RE rail)
- E_r = rail modulus of elasticity, 2.1×10^6 kg/cm^2 (30×10^6 $lb./in.^2$)

TABLE 7.1
EFFECTS OF UNBROKEN RAIL AND COLUMN LONGITUDINAL STIFFNESS ON LOADS TRANSFERRED TO THE SUBSTRUCTURE [5]

Column Stiffness (lb/in.)	Medium Restraint		High Restraint	
	Load (lb)	Gap Size* (in.)	Load (lb)	Gap Size* (in.)
Rigid	131,000	0.67	134,000	0.79
500,000	50,600	0.89	35,800	0.89
100,000	17,700	1.17	11,600	0.96
40,000	9,300	1.27	5,800	1.15

* Assuming a symmetrical girder bearing configuration of E—F/F—E/E—F and a 60° F temperature drop.

A simplified form of Equation 2 has been used to estimate rail gap size, based on a length, L, on either side of the break over which full rail anchorage is provided, so that:

$$G = (\alpha\Delta T)^2 \; A_r E_r / R_f \qquad \text{(Eqn. 3)}$$

where R_f is the longitudinal restraint per centimeter of rail in kilograms per centimeter (pounds per inch).

Equation 2 provides a reasonable estimate of rail gap size for medium- and high-restraint fasteners, but significantly underestimates the rail gap size for low-restraint fasteners. Low-restraint fasteners generally do not adequately control the size of the rail gap. Equation 3 provides relatively accurate estimates in many cases, except where high-restraint fasteners are used. Improved accuracy can be obtained with Equation 2 if the term X_{c2} is modified to use the estimated total number of fasteners over which the locked-in load is distributed. Therefore:

$$G = 2(X_{c1} + X_{c2} - X_{c3}) \qquad \text{(Eqn. 4)}$$

where:

X_{c2} = $0.5\, \alpha\Delta T\, n_x L_s$

n_x = $P_T/P_{fmax} = P_{fmax}K_r/2P_T K_f$

P_T = $\alpha\Delta T\, A_r E_r$, the thermal load, kg (lb.)

P_{fmax} = $(n_{ns}P_{fns} + n_s P_{fs})/(n_{ns} + n_s)$, the average fastener restraint limit kg (lb.)

K_r = $A_r E_r / L_f$, the rail spring, kg/cm (lb./in.)

K_f = fastener longitudinal stiffness kg/cm (lb.in.)

Equations 2 and 3 estimate rail gap size assuming linear load distributions. Typically, finite-element computer models show the fastener load distributions to be nonlinear. Refer to **Figure 7.5.3** for the rail gap sizes predicted using a finite-element model.

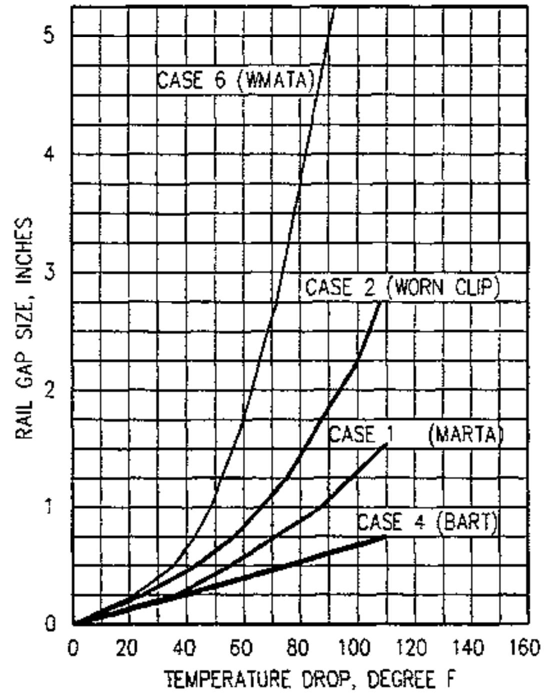


Figure 7.5.3 Rail Break Gap Size Predicted by Finite Computer Model [5]

Table 7.2 summarizes estimated rail gap size using different equations and software.

Once the rail gap size has been estimated, the variables affecting the magnitude of the gap (such as rail fastener spacing and stiffness) should be adjusted to limit the size of the gap. This will minimize the chance of a light rail vehicle derailment caused by a rail gap. The size of the rail gap is usually limited based on the diameter of the vehicle's wheel. Typically accepted rail gaps are in the range of 50 millimeters (2 inches) for a 400-millimeter (16-inch) diameter wheel. [4]

It is interesting to note that efforts to control rail gap size offer opposing solutions. For safety reasons, the length of the rail gap should be minimized to reduce the possibility of a derailment. In addition, the forces and

TABLE 7.2
COMPARISON OF RAIL BREAK GAP SIZE BY DIFFERENT FORMULAS[5]

Rail Break Gap Size Estimates (in.)						
Case	Equation 2	Equation 3	Equation 4	TBTRACK[b] $\Delta T_g = 0$	TRKTHRM[b] $\Delta T_g = 0$	TRKTHRM[b] $\Delta T_g = 60$
1	0.69	0.62	0.83	0.55	0.74	0.67
2	0.72	1.23	1.35	0.85	1.29	1.31
3	0.89	1.23	1.55	0.97	1.38	1.47
4	0.51	0.15	0.99	0.40	0.50	0.79
5	0.57	0.62	0.68		0.66	0.63
6	0.85	2.29[a]	2.47	1.77	2.39	2.68
7	0.82	1.43[a]	1.62		1.54	1.61
8	1.21	0.68	1.44		1.20	1.14

Note: ΔT_g = Temperature change in the girder; the girder bearing configuration = E-F/F-E/E-F; the length of the span = 80 ft.; the length of the fastener = 30 in.; and the temperature change in the rail = 60° F (temperature drop).

[a] Using average of $R_f = n_s P_{fs} + n_{ns} P_{fns})/(n_s + n_{ns})$ where n_s = the number of slip fasteners, and n_{ns} = the number of non-slip fasteners.

[b] TBTRACK and TRKTHRM are programs developed to calculate rail-break gap size.

moments transferred to the structure due to a rail break should be minimized to achieve an economical structure. To resolve safety issues, fasteners with relatively high longitudinal restraint should be used. To address the structural issues, fasteners with a relatively low longitudinal restraint should be used. The trackwork and structural engineers must coordinate the opposing design requirements to balance the needs for each transit system.

7.5.5 Terminating CWR on Aerial Structures

As much as possible, CWR should not be terminated on an aerial structure due to the large termination force transferred to the structure. Problems arise when specialwork must be located on an aerial structure due to the length of the structure, the needs of the transit operations, or other occurrences. Unbalanced thermal forces exist in specialwork locations due to discontinuities in the rail. Standard turnout units, by design, transfer high forces through the units on an aerial structure which causes misalignment and wear.[12]

To accommodate the large forces occurring at locations of specialwork, rail anchors or rail expansion joints could be used. Rail anchors create a zero force condition through the specialwork, but pass the rail termination force to the structure. The massiveness of the resulting substructure, however, may be aesthetically and economically undesirable. The use of sliding rail expansion joints must consider the following:

- The construction length of the sliding rail joints
- The length of structure required to accommodate the specialwork and sliding rail joint
- The design, location, and installation details of the rail anchors

Some transit systems have used a tie bar device to accommodate specialwork on their aerial structures. See **Figure 7.5.4** for a picture of a tie bar installation at an aerial structure crossover.

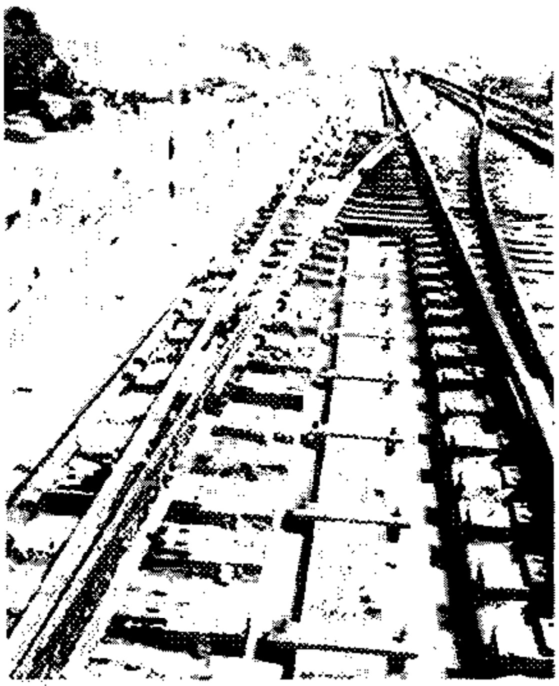


Figure 7.5.4 Tie Bar on Aerial Crossover[6]

With a tie bar system, the CWR is interrupted at the crossover and the rail ends are attached as rigidly as possible to special "AXO" girders adjacent to the outer ends of the specialwork. The AXO girders are similar to standard girders except for the addition of an embedded steel plate to which the tie bar is attached by welding. The tie bar, a structural steel member with a cross section equal to two rails, is located on the centerline of each track and is welded to the embedded plates on the centerline of the two AXO girders. The tie bar rests on Teflon bearing pads placed directly on the concrete deck for the length of the crossover.

When the temperature changes, the thermal force built up at the end of the CWR is transferred to an AXO girder through a group of rail fasteners equally spaced along the girder. An equal and opposite thermal force is developed in the tie bar and transferred to the AXO girder through a welded connection. Therefore, the net longitudinal thermal force is directed through the tie bar instead of the piers or the specialwork, where the trackwork could be damaged.

Designers should avoid specialwork on aerial structures. When this cannot be avoided, there are ways to accommodate the specialwork without causing it to malfunction.

7.5.6 Types of Deck Construction

Traditionally, three distinctly different types of deck construction have been used in rail transit construction. The earliest elevated transit track featured open deck construction, where timber crossties were attached directly to the steel superstructure. This type of construction was used to eliminate the cost and dead load of the ballast, as well as the deck structure required to support/contain the ballast. Ballast deck construction was then used to address the public's complaints about the noise and vibration generated by the transit vehicles as they traveled along the open deck structures, among other issues. Over the last 30 years, a mixture of ballast deck and direct fixation deck construction has been used. The direct fixation deck was developed to resolve the shortcomings of the ballast deck.

The decision concerning which type of deck construction to use with CWR has profound construction cost implications. Based on the difference in cost of aerial structures with and without CWR and the resultant thermal effects considered in the structural design, the most conservative design using CWR could increase structure costs by 23 percent.[5] But there are many variables to consider when choosing the type of deck to use on any particular transit structure.

7.5.6.1 Ballast Deck Construction

Ballast deck construction is still considered a valuable choice by some transit agencies. It is usually used on moderate length bridges, generally 91 meters (300 feet) or less. Advantages of the ballast deck include:[2, 4, 10]

- Provides an intermediate cushion between the rails and the structure to enhance ride quality
- Limits the thermal forces associated with rail/structure interaction
- Uses typical rail track fasteners
- Reduces noise and vibration
- Permits standard track maintenance to adjust alignment and profile
- Provides good live load distribution
- Offers good track support

Disadvantages of the ballast deck include:

- The cost of deck waterproofing and the ballast layer
- The heavy deck load
- The greater depth of deck required
- The cost of maintenance of the ballast layer, including cleaning and tamping (although not light rail, some Japanese railways require maintenance and tamping operations on their ballast deck structures two to three times a year. In addition, their overall maintenance costs for ballast deck structures is approximately five times greater than for direct-fixation structures [13])
- The development of rail breaks with horizontal, vertical, and angular displacements

7.5.6.2 Direct Fixation Deck Construction

Direct fixation deck construction has now become the accepted standard practice for many transit properties. Developed in the 1960s for new light rail transit projects, the rails are attached directly to the concrete deck by elastic fasteners. The advantages of this type of construction include:[2, 10]

- Elastic fasteners absorb noise and vibration and provide vertical flexibility
- Improves aesthetics by using shallower, less massive structures
- Generates a relatively low dead load
- Rail fasteners provide electrical isolation and a means to efficiently adjust the line and grade of the track
- Requires less maintenance and is easier to maintain
- Retains track geometry much longer than ballasted track
- Provides relatively good ride quality
- Offers relatively good live load distribution

The use of direct fixation track construction has been credited with saving millions of dollars on a transit project by eliminating the need for crossties and ballast.[14] MTA New York City Transit discusses the difficulty in identifying any specific increased cost for the rail/structure interaction associated with the thermal effects.[9] The construction cost impacts are unclear since thermal forces are combined with live loads, dead loads, and other loads in various combinations according to the design codes and criteria.

Disadvantages of direct fixation deck include:

- Rail/structure interaction must address thermal forces
- High initial cost
- Tight construction control required
- Specialized rail fasteners required

Although direct fixation deck is presently the most common construction method on light rail transit structures, it is clear that the decision to use ballast deck or direct fixation deck construction on a transit property's aerial structures is based on technical requirements, aesthetics, construction cost, maintenance cost, and individual preference.

7.6 DIRECT FIXATION FASTENERS

Since the majority of transit properties now use CWR with direct fixation deck construction, the aerial structure designer should understand the types of rail fasteners presently available. Rail fasteners secure the CWR to the deck of the aerial structure; the bottom portion of the fastener is bolted to the deck and the top portion is bolted or clipped to the bottom flange of the rail.

Low-restraint, moderate-restraint, and high-restraint fastener clips are available. In addition, some transit properties have utilized zero longitudinal restraint (ZLR) fasteners in certain circumstances. Although ZLR fasteners allow the superstructure to move longitudinally without generating thermal interaction forces, the rail gap size at a rail break has to be carefully considered when it is used.

With a conventional direct fixation fastener, the elastomer provides isolation of the high wheel/rail impact forces from the deck; electrical isolation; vertical elasticity to dampen noise and vibration; longitudinal elasticity to accommodate rail/structure interaction movements; and distribution of the wheel loads longitudinally along the rail. The fastener also provides full restraint in the lateral direction, maintains the desired rail tolerances, and prevents rail buckling under high temperature. The level of longitudinal restraint chosen for the fastener is a compromise between the restraint required to limit the rail gap size and the desire to minimize rail/structure interaction forces.[6, 8]

The following are typical ranges of direct fixation fastener properties:

- Vertical fastener stiffness:
  13,300 to 26,600 N/mm
  (75,000 to 150,000 lb./in.)
- Lateral fastener stiffness:
  3,900 to 11,400 N/mm
  (22,000 to 64,000 lb./in.)
- Longitudinal fastener stiffness
  600 to 3,200 N/mm
  (3,400 to 18,000 lb./in.)
- Longitudinal restraint
  9,000 to 15,750 N
  (2,000 to 3,500 lb.)

Direct fixation fasteners are commonly spaced at 762 millimeters (30 inches) on center. This spacing is determined by analysis of rail bending stresses, interaction forces of the rail and rail fasteners, and the rail gap size at a rail break location. Trackwork and structural engineers need to carefully coordinate fastener spacing on sharply skewed bridges to ensure that the fasteners are adequately supported on each side of the joints in the deck.

Most light rail transit systems use a concrete pad, or plinth, to support the direct fixation fasteners and attach them to the superstructure. Intermittent gaps are provided along the length of the plinths to accommodate deck drainage and to provide openings for electrical (systems) conduits placed on the deck.

Reinforcing steel dowels project from the bridge deck, anchoring the second-pour concrete plinths to the deck. Alternately, threaded female inserts are embedded in the concrete deck and threaded reinforcing steel is installed prior to pouring the plinths. In addition, the deck slab is usually recessed for the second-pour plinths, forming a shear key to help resist the lateral loads from the rail and vehicles. The installation of direct fixation trackwork requires tight tolerances for the support structure The second-pour concrete plinths are carefully constructed to meet the alignment and profile requirements of the CWR and fasteners.

7.7 TYPES OF SUPERSTRUCTURE

During the early stages of design, the designer must determine the type of superstructure to be used for a specific aerial transit structure. Whether the superstructure is comprised of steel or concrete girders, as well as the configuration of the girders, must be evaluated with respect to the project and site constraints.

Commonly considered superstructure types include:

- Cast-in-place concrete
- Precast concrete
- Segmental precast concrete
- Steel girders with cast-in-place or precast deck slab
- Steel box section with either cast-in-place or precast deck

The following factors are used to comparatively study superstructure types:[1, 4, 15]

- Effectiveness of structural function (span lengths, vertical clearances, span-to-depth ratio, etc.)
- Constructibility issues, such as erection and construction convenience, including transportation of the structural elements to the site
- Production schedule constraints
- Capital cost
- Maintenance cost
- Availability of materials and finished product
- Availability of construction expertise
- Site working conditions, including weather, local ordinances, and working restrictions
- Aesthetics
- Owner's preference
- Urban constraints
- Durability
- Construction schedule

For comparison of the many variables involved in evaluating a type of superstructure, a structural system was selected that includes a cast-in-place reinforced concrete slab supported by standard precast, prestressed concrete girders, whose substructure included concrete pier columns and a concrete footing (see **Figure 7.7.1**). The goal is to select a span length that minimizes the sum of the construction costs for the deck, girders, and substructure. The cost optimization effort can be based on a typical span or an entire transit line.[16]

The relative costs of different structural components considered for each span are shown as plots of cost versus span length in **Figures 7.7.2** through **7.7.8**. Although this comparison was performed in 1976, the following conclusions still apply to present aerial structure design efforts:

- Economically attractive span lengths vary from 9 meters (30 feet) to 21.4 meters (70 feet).
- The effect of beam spacing increases with span length; within other design constraints, the largest beam spacing possible should be used.

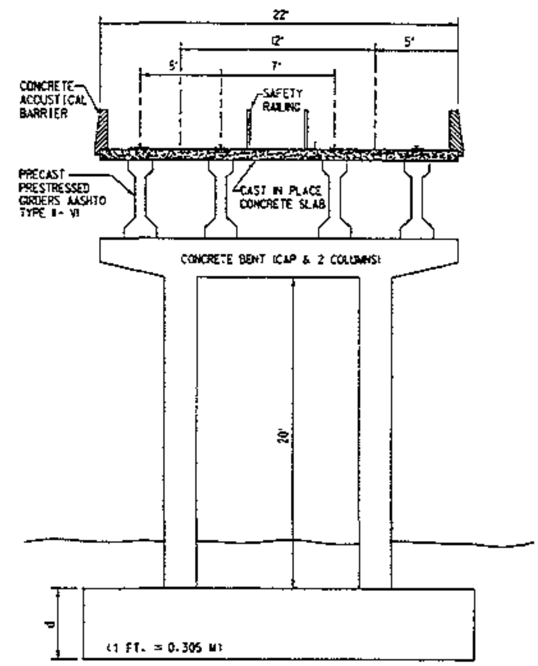


Figure 7.7.1 Typical Section of Elevated Structure Studied [16]

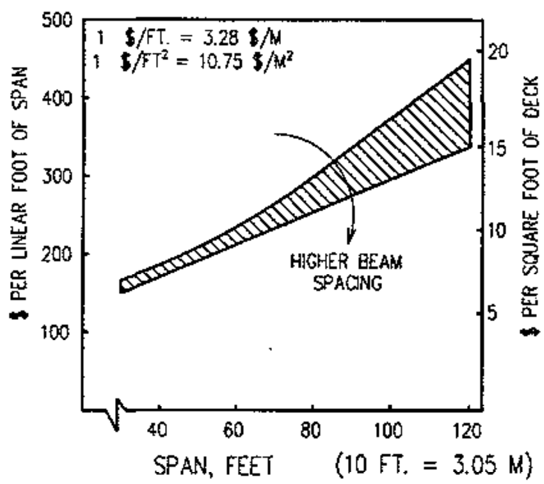


Figure 7.7.2 Range of Deck Costs as a Function of Span Length and Beam Spacing of Structure [16]

- In poor soil conditions, foundation costs increase sharply with increasing span length, up to a point where deep foundations should be considered instead of spread footings; therefore, shorter spans are recommended when unfavorable soil conditions exist and spread footer foundations are more economical.

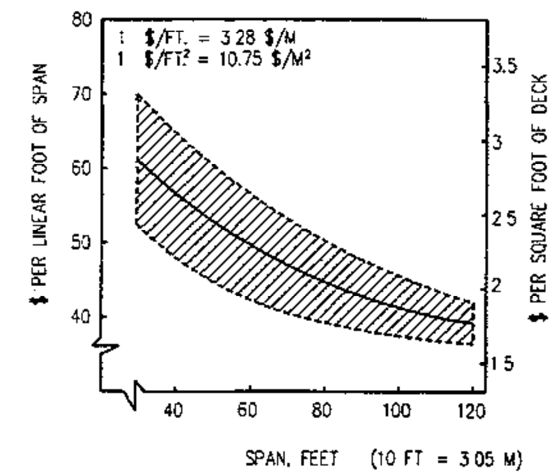


Figure 7.7.3 Range of Supporting Bent Costs as a Function of Span Length of Structure [16]

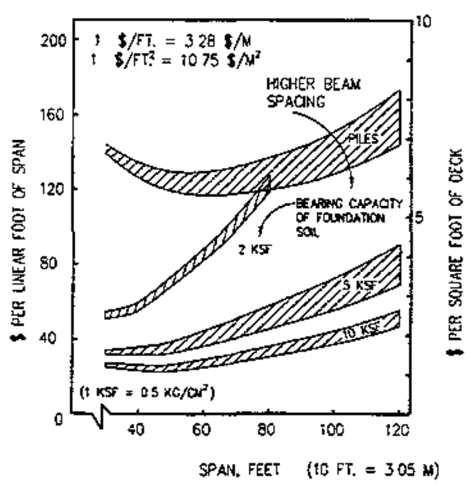


Figure 7.7.4 Range of Foundation Costs for Different Soil Conditions as a Function of Span Length of Structure [16]

- The minimum cost span derived from minimizing the total construction cost is generally different than that obtained by minimizing the cost of one component (deck, girders, substructure, or foundations).

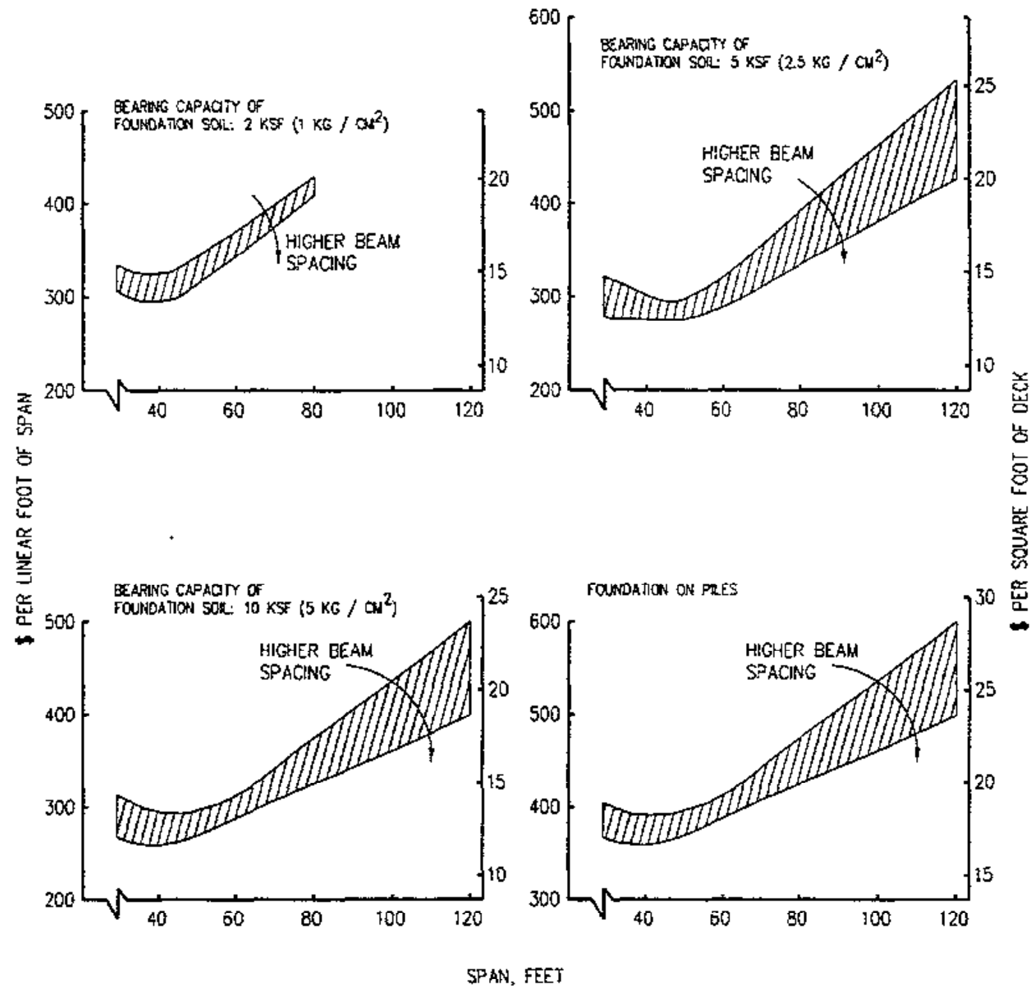


Figure 7.7.5 Range of Total Costs of Elevated Structural System as a Function of Span Length for Different Soil Conditions [16]

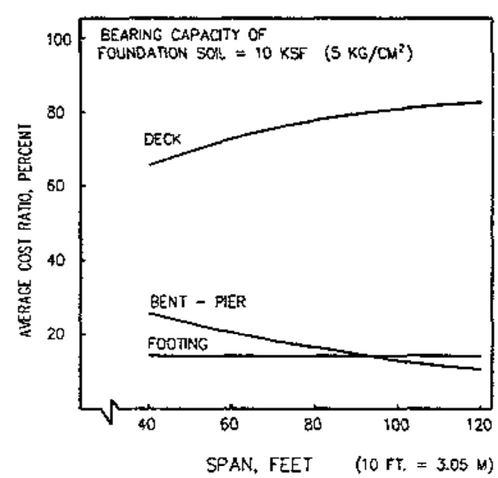


Figure 7.7.6 Average Ratio of Cost of Each Structural Subsystem to Total Cost of Structure—Founded in Good Soils [16]

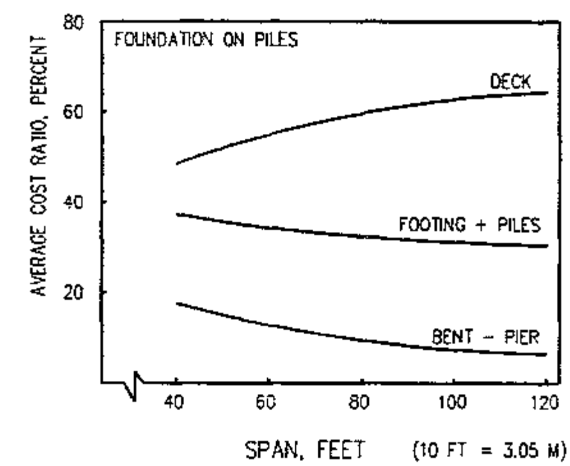


Figure 7.7.7 Average Ratio of Cost of Each Structural Subsystem to Total Cost of Structure—Founded in Poor Soils [16]

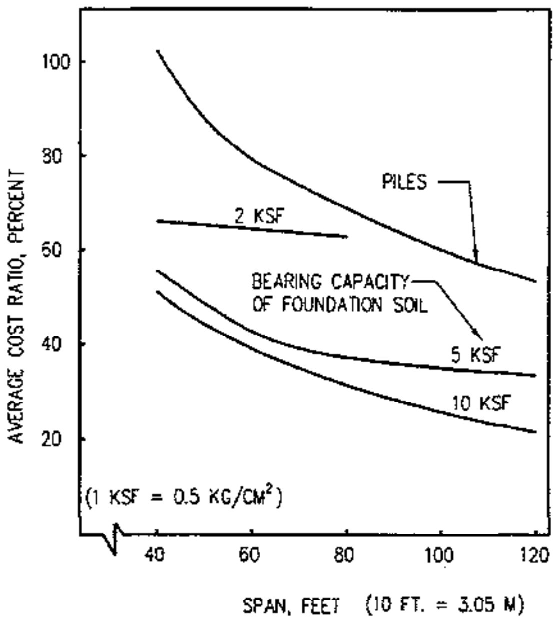


Figure 7.7.8 Average Ratio of Cost of Supporting Structure and Foundation to Cost of Deck Structure for Different Soil Conditions *[16]*

It is important to note that in planning for aerial structures, any economical span range can be considered in the design. The final span length selection should be weighted by other considerations such as aesthetics and community factors.

Many times in an urban setting, the span lengths are specified that provide the required horizontal and vertical clearances to existing facilities along the light rail system's alignment. The location of existing railroad tracks, roadways, highway bridges, waterways, and major utilities can restrict substructure locations, thereby limiting the choices for span lengths.

As part of a preliminary design effort for an aerial structure, a study should be performed to determine the most desirable structure configuration based on economic, social, environmental, and technical needs.

7.8 REFERENCES

[1] Harrington, G., Dunn, P.C., *Investigation of Design Standards for Urban Rail Transit Elevated Structures*, UMTA, June, 1981.

[2] Niemietz, R.D., Neimeyer, A.W., *Light Rail Transit Bridge Design Issues*, Transportation Research Board, Light Rail Transit: Planning, Design, and Operating Experience, Transportation Research Record No. 1361, 1992.

[3] Nowak, A.S., Grouni, H.N., "Development of Design Criteria for Transit Guideways", *ACI Journal*, September-October, 1983.

[4] ACI Committee 358, *Analysis and Design of Reinforced Concrete Guideway Structures*, ACI 358.1R-86.

[5] Ahlbeck, D.R., Kish, A., Sluz, A., *An Assessment of Design Criteria for Continuous-Welded Rail on Elevated Transit Structures*, Transportation Research Board, Rail Track and Structures, Transportation Research Record No. 1071, 1986.

[6] Clemons, R.E., *Continuous Welded Rail on BART Aerial Structures*, Transportation Research Board, Rail Track and Structures, Transportation Research Record No. 1071, 1986.

[7] Grouni, H.N., Sadler, C., *Thermal Interaction of Continuously Welded Rail and Elevated Transit Guideways*, Ontario Ministry of Transportation and Communications.

[8] Guarre, J.S., Gathard, D.R., *Implications of Continuously Welded Rail on Aerial Structure Design and Construction*, June, 1985.

[9] New York City Transit Authority, Metropolitan Transportation Authority, *Continuous Welded Rail on Elevated Structures*, August, 1991.

[10] Clemons, R.E., *Continuous Welded Rail on Aerial Structure: Examples of Transit Practice*, APTA, January, 1985.

[11] Fine, D.F., *Design and Construction of Aerial Structures of the Washington Metropolitan Area Rapid Transit System*, Concrete International, July, 1980.

[12] Lee, R.J., *Designing Precast Aerial Structures to Meet Track and Vehicle Geometry Needs*, 1994 Rail Transit Conference.

[13] Eisenmann, J., Leykauf, G., Mattner, L., "Recent Developments in German Railway Track Design," *Proceedings of the Institution of Civil Engineers*, Transport. Vol. 105, No. 2 (May, 1994)

[14] Meyers, B.L., Tso, S.H., "Bay Area Rapid Transit: Concrete in the 1960s", *Concrete International*, February, 1993.

[15] Desai, D.B., Sharma, M., Chang, B., *Design of Aerial Structure for the Baltimore Metro*, APTA Rapid Transit Conference, June 1986.

[16] Naaman, A.E., Silver, M.L., "Minimum Cost Design of Elevated Transit Structures", *Journal of Construction Division*, March, 1976.

[17] Fassmann, S., Merali, A.S., *Light Rail Transit Direct Fixation Track Rehabilitation: The Calgary Experience*, Transportation Research Board, Light Rail Transit: Planning, Design, and Operating Experience, Transportation Research Record No., 1361, 1992.

[18] *AREA Manual for Railway Engineering*, Section 8.3, "Anchorage of Decks and Rails on Steel Bridges," 1995

[19] Beaver, J.F., *Southern Railway System's Use of Sliding Joints*, AREA Bulletin 584, February, 1964

[20] Billing, J.R., Grouni, H.N., *Design of Elevated Guideway Structures for Light Rail Transit*, Transportation Research Record, Journal 627, 1977.

[21] Casey, J., "Green Light", *Civil Engineering*, May, 1996.

[22] Deenik, J.F., Eisses, J.A., Fastening Rails to Concrete Deck, The Railway Gazette, March 18, 1966.

[23] Dorton, R.A., Grouni, H.N., *Review of Guideway Design Criteria in Existing Transit System Codes*, ACI Jounral, April 1978.

[24] Fox, G.F., *Design of Steel Bridges for Rapid Transit Systems*, Canadian Structural Engineering Conference, 1982.

[25] International Civil Engineering Consultants, Inc., *Task Report on a Study to Determine the Dynamic Rail Rupture Gaps Resulting from a Temperature Drop for BART Extension Program*, July 26, 1991.

[26] Jackson, B., "Ballastless Track, A Rapid Transit Wave of the Future?", *Railway Track and Structures*, April, 1984.

[27] Kaess, G., Schultheiss, H., "Germany's New High-Speed Railways, DB Chooses Tried and Tested Track Design", *International Railway Journal*, September, 1985.

[28] Magee, G.M., *Welded Rail on Bridges, Railway Track and Structures*, November, 1965.

[29] Mansfield, D.J., "Segmental Aerial Structures for Atlanta's Rail Transit System", Transportation Research Board, *Rail Track and Structures*,

Transportation Research Record No. 1071, 1986.

[30] "Philadelphia's El Gets Major Facelift", *Mass Transit*, May/June, 1995.

[31] McLachlan, L.J., "University Boosts Light Rail Traffic", *Developing Metros*, 1994.

[32] Middleton, W.D., "Engineering the Renaissance of Transit in Southern California", *Railway Track and Structures*, March, 1993.

[33] Middleton, W.D., "DART: Innovative Engineering, Innovative Construction", *Railway Track and Structures*, December, 1994.

[34] Patel, N.P., Brach, J R., "Atlanta Transit Structures", *Concrete International*, February, 1993.

[35] PBQD, *Rail/Structure Interaction Analysis - Retrofit of Direct Fixation Fasteners with Spring Clips, WMATA - Rhode Island Avenue*, February, 1995.

[36] PBQD, Thermal Study of Bridge-Continuous Rail Interaction, Metro Pasadena Project, Los Angeles River Bridge, August, 1994.

[37] Swindlehurst, J., "Frankford Elevated Reconstruction Project," *International Bridge Conference*, June, 1984.

[38] Thorpe, R.D., *San Diego LRT System: Ten Years of Design Lessons*, Transportation Research Board, Light Rail Transit, Planning, Design, and Operating Experience, Transportation Research Record No. 1361, 1992.

[39] Varga, O.H., *The Thermal Elongation of Rails on Elastic Mountings*, AREA Bulletin 626, February, 1970.

[40] Yu, S., "Closing the Gaps in Track Design," *Railway Gazette International*, January, 1981.

[41] Zellner, W., Saul, R., "*Long Span Bridges of the New Railroad Lines in Germany, Bridges: Interaction Between Construction Technology and Design.*"

Chapter 8—Corrosion Control

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CHAPTER 8—CORROSION CONTROL

8.1 GENERAL

Electrified rail transit systems, both light and heavy rail, typically utilize the track system as the negative side of an electrical circuit in the system's traction power network. In light rail transit systems, the positive side, which carries DC electrical current from the substation to the transit vehicle, is typically an overhead contact wire system or catenary. Because perfect electrical insulators do not exist, electrical currents will leak out of this circuit and escape into the soil to find the path of least resistance back to the substation. The amount of such stray currents will be inversely proportional to the efficiency of the electrical insulation provided and directly related to the conductivity of the soil and any alternative current paths back to the substation such as pipes, cables, reinforcing steel, etc.

Typically, unless a fault has occurred in an insulator, stray currents from the positive side of the light rail transit traction power circuit are minuscule. Stray currents from the track, on the other hand, are common and can get quite large due in no small part to the proximity of the track to the ground. Once in the soil, stray currents will follow any available conductor to get back to the traction power substation. These paths can include the soil itself, buried utility pipelines and cables, or other metallic structures, such as bridges, along the way. If an alternative path offers less electrical resistance than another route, then the better conductor will carry proportionally more of the stray current. In extreme examples, particularly when the electrical continuity of the track structure is poor, more electricity will return as stray current than through the running rails. Some older elevated systems were actually designed for this occurrence.

The problem with stray currents evolves from the fact that whenever electric current leaves a metallic conductor (i.e., a water pipe) and returns to the soil (perhaps because it is attracted to a nearby gas line), it causes corrosion on the surface of the conductor it is leaving. This is the same phenomenon that occurs when a metallic object is electroplated, such as when construction materials are zinc plated. In the case of stray currents, the typical current path can involve several different conductors as the electricity wends its way back to the substation; therefore corrosion can occur at multiple locations. This can create conditions that range from leaking water lines to gas line explosions. The rail itself will also corrode wherever the current jumps from it to reach the first alternative conductor. Structures along the transit line, particularly steel bridges and embedded reinforcing steel, are also at risk. Hence, multiple parties have an interest in controlling or eliminating the leakage of stray currents and minimizing the damage they inflict.

Stray currents are common on a light rail transit system because its track structures are typically close to the ground. Grade crossings, embedded track, and fouled or muddy ballast are common locations for propagation of stray currents. Because of the maze of underground utility lines typically found in urban and suburban areas where light rail transit systems are built, abundant alternative electrical paths exist. Predicting the likely path of potential stray currents and defining methods to protect against them can be extremely complex. Because of this complexity, it is essential that the advice of a certified corrosion control specialist with stray current experience be sought from the beginning of design.

In his book Corrosion Engineering, Mars G. Fontana states:

> *"...The term stray current refers to extraneous direct currents in the earth. If a metallic object is placed in a strong current field, a potential difference develops across it and accelerated corrosion occurs at points where current leaves the object and enters the soil. Stray current problems were quite common in previous years due to current leakage from trolley tracks. Pipelines and tanks under tracks were rapidly corroded. However, since this type of transportation is now obsolete, stray currents from this source are no longer a problem."* [1]

This text requires updating since the "trolley tracks" have evolved into light rail transit (LRT) lines and the stray currents from LRT will re-introduce potential corrosion problems.

Some of the principal measures that can be taken to minimize traction current leakage include:

- If jointed track is used, install electrical bonding across the joints. One of the many advantages of continuous welded rail (CWR) is that it offers a superior traction power return.
- Insulate rails from their fastenings and encase rails in embedded track in an insulating material. The steel reinforcement in the underlying concrete slab can be continuously welded to act as a stray current collector.
- In ballasted track areas the ballast should be clean, well-drained and not in contact with the rail.
- Conduct corrosion surveys on susceptible metal structures before service begins and perform regular monitoring and maintenance afterwards.
- Provide auxiliary conductors to improve the ampacity of the rail return system. This can be accomplished by connecting all rails together or by adding cable conductors.

Existing pipes and cables in the vicinity of the tracks must be investigated and protective action taken as necessary to protect them from stray current corrosion.

Whether the light rail operator or the local utility takes responsibility, it is imperative that strategic action is required to mitigate the effects of stray current corrosion in the design phase and during construction. This will avoid corrosion from becoming a costly and dangerous maintenance issue later.

8.2 TRANSIT STRAY CURRENT

8.2.1 Stray Current Circuitry

Traction power is normally supplied to light rail vehicles (LRV) by a positive overhead catenary system. The direct current is picked up by a vehicle pantograph to power the motor and then returns to the substation via the running rails, which become the negative part of the circuit. Unfortunately, a portion of the current strays from the running rails and flows onto parallel metallic structures such as reinforcing steel, utility pipes and cables, and other structures such as pilings, ground grids, and foundation reinforcing bars.

8.2.2 Stray Current Effects

Corrosion of metallic structures is an electrochemical process that usually involves small amounts of direct electrical current (dc). It is an "electro" process because of the flow of electrical current. It is a "chemical" process because of the chemical reaction that occurs on the surface and corrodes the metal. One ampere of direct current flowing for 1 year will corrode 20 pounds of iron, 46 pounds of copper, or 74 pounds of lead. Natural galvanic corrosion involves milliamperes of current so many buried structures can last several years before structural failure.

Unlike the very small currents associated with galvanic corrosion, stray current corrosion from a transit system can involve several hundred amperes. The same physical laws apply for corrosion of the metal, electron flow, chemical reactions, etc., but metal loss is much faster because of the larger amounts of current involved. For example, with 200 amperes of current discharging from an underground steel structure, 2 tons of metal will be corroded in 1 year (20 pounds per ampere per year x 200 amperes = 4,000 pounds of steel corroded).

Thus, stray current from a light rail system will corrode transit rails, rebar, and steel structural members and all adjacent underground metallic structures unless protective measures are provided.

8.2.3 Design Protection Components

The phenomenon of stray currents from electrified street railways was first observed when trolley systems were constructed in the 1880s. The importance of maintaining good electrical continuity of the rails was quickly recognized and many trolley systems welded rail joints 60 years before the process was widely accepted on "steam" railroads. Where rails could not be welded, they were electrically bonded to each other with copper cables. These measures reduce stray currents, but cannot eliminate them. No matter how good a conductor the track system is, some portion of the traction power current will always seek an alternative path back to the substation.

Utility companies fought this problem, both in the courts and in the field. Once the legal issues were resolved, the most effective means of minimizing stray current damage was to make the buried utility network as electrically continuous as possible. Copper bonds were placed around joints in buried pipes and crossing utility lines were electrically bonded to each other. Finally, the entire utility network was directly connected to the negative bus of the traction power substation by "drain cables" so that any stray currents could return without causing significant corrosion along the way. All big city utility companies participated in a "corrosion control committee" with the trolley company to ensure that all new facilities were properly integrated into the system, thereby preserving the delicate balance of the network. (Since in many cities, a single holding company might own most of the utility companies and the trolley company as well, such committees were not necessarily combative congregations.) Such methods were generally effective; however a side effect of the improved underground electrical continuity was that the utility grid typically became better bonded than the track structure. As such, a significant portion of the traction power current would perversely elect to stray from the rails and use the buried utilities to get back to the substation.

When trolley systems were abandoned in most cities, the corrosion committees were disbanded and the utility companies became less zealous about bonding their networks. In many cases, the introduction of non-metallic piping created significant electrical discontinuities in utility systems. Such gaps were of no consequence in a city without a local originator of significant stray currents and associated corrosion protection measures. With no trolley network in the neighborhood, corrosion potential could typically be neutralized using sacrificial anodes. However, if a light rail system is introduced into such a city, the sacrificial anodes are insufficient. The result can be corrosion problems not unlike those that occurred a hundred years ago with stray currents leaping off metal pipes when they reach an electrical dead-end at a non-metallic conduit.

Reverting to the continuous utility bonding and drain cable methods of the past is typically not a completely effective methodology of achieving stray current control. Because of the widespread use of non-metallic buried pipe, and the subsequent high expense of re-creating an electrically continuous path through the utilities, it is typically much cheaper—and arguably easier—to attempt to effectively insulate the track structure from the ground so that stray currents are minimized from the beginning. Such insulation, coupled with other protective measures, including selective bonding of utilities and drain cabling, is the foundation of stray current corrosion control measures of modern light rail transit systems. This controlled approach also protects rails and other transit structures that would be subjected to these stray currents.

8.2.3.1 Traction Power

Since the 1960s increased efforts to reduce stray currents have been made through modifications to traction power substations. Typical modern substations are either ungrounded or "floating" above ground potential, or are grounded through diodes that prevent stray currents from passing from the negative bus to the ground. This frequently reduces stray currents from hundreds of amperes to near zero. Completely ungrounded systems exhibit the greatest improvement in stray current control. Nevertheless, stray currents are still possible in an ungrounded system as the electricity can leave and return to the track structure from the ground. It is entirely possible for current to leak out of the track, travel along alternative paths in the ground, and then return to the track at another location. Since the track itself must eventually be directly connected to the negative substation bus, stray currents can circumvent substation isolation systems.

8.2.3.2 Track and Structure Bonding

Achieving electrical continuity of the track structure is of paramount importance in keeping negative return current in the rails. The use of continuously welded rail, together with the installation of bonding cables around unavoidable bolted joints, provides most rail transit systems with an excellent current path through the rails. Stray current corrosion of transit structures can typically be controlled through electrical bonding. Since the 1960s, it has been common practice to also bond reinforcing steel in concrete structures so as to provide a continuous electrical path. The bonding is typically concentrated in reinforcing bars in the lowest portions of the structure and those surfaces in contact with rail such as retaining walls.

Many light rail systems have been built with heavily reinforced slabs beneath the track to provide both structural support and a barrier against migration of stray currents into the ground. Bonded reinforcing steel networks can provide a shielding effect for outside utility structures.

8.2.3.3 Drain Cables

Drain cables are sometimes provided for future use on modern light rail systems, but are not necessarily connected to the utility system. Utility companies monitor their pipelines for any stray currents and, if problems are detected, they have the option of connecting to the drain cable as a last resort. Coupled with other protective systems, such cabling provides a secondary approach to corrosion protection in the event that the primary measures are ineffective at locations where excessive leakage from the rails occurs.

8.2.3.4 Trackwork

Ultimately, electrical insulation of the track structure offers the first line of defense against stray currents. Keeping the rails clean and dry is important, as is good insulators between the rail and the ties. Good drainage is also critical. Rail laid in streets may also have insulating coatings to maintain electrical isolation. Since track design is the focus of this handbook, track insulation will be discussed in detail in Section 8.3. It must be emphasized, however, that track insulation is not a panacea, particularly if the track insulation systems are not regularly maintained and cleaned. If track insulation systems are compromised, such as by fouled ballast or dirty insulators, stray current leakage is inevitable. Thus, the required level of maintenance should be considered during design.

8.3 TRACKWORK DESIGN

LRT systems utilize dc electrical power that is normally returned from the LRV to the substations through the rails. Stray current control is a necessary element in the design of the track system. Modern designs for dc transit systems include the concept of "source control" at the base of the rail or rail surface to minimize the generation of stray currents. The route of an LRT system is not generally within a totally dedicated right-of-way; therefore, the various types of rail construction each require individual attention. Electrical isolation of the rail using insulation is necessary for utility pipelines and steel structures.[2] In addition, if the track is shared by railroad freight traffic during non-revenue hours, insulated rail joints are required at all rail sidings and connections to adjacent rail facilities.

The essence of state-of-the-art technology in the design of modern transit systems is the concept of controlling stray current at the rails. Operation of the traction power system with the substation negatives isolated from ground (floating) will result in a higher overall system-to-earth resistance. The goal is to maximize the conductivity of the rail return system and the electrical isolation between the rails and their support systems.

The following are generally accepted design measures for the various track types to create an electrically isolated rail system that controls stray currents at the source:

- Continuous welded rail
- Rail bond jumpers at mechanical rail connections (especially special trackwork)
- Insulating pads and clips on concrete crossties
- Insulated rail fastening system for timber crossties and switch timber
- Maintaining a minimum separation of 25 millimeters (1 inch) between the bottom of the rail and the ballast on ballasted track
- Insulated direct fixation fasteners on concrete structures
- Coating the rail with coal tar epoxy or other insulating material at all roadway and pedestrian crossings
- Coating embedded rails with an insulating material and encasing the track slab with an insulating membrane

- Providing an insulated rubber boot around the rail in embedded sections
- Cross-bonding cables installed between the rails to maintain equal potentials of all rails and reduce resistance back to the substation
- Insulation of the impedance bond tap connections from the housing case
- Insulation of switch machines at the switch rods
- Installation of rail insulated joints to isolate rail-mounted bumping posts
- Installation of insulated rail joints to isolate the main line from the yard and the yard from the usually grounded maintenance shop area
- Separate traction power substations to supply operating currents for the main line, yard and shop
- Rail insulated joints to isolate the main line rails from freight sidings or connections to other rail systems

8.3.1 Rail Continuity

Continuous welded rail is the generally accepted standard for main line light rail construction. CWR creates an electrically continuous negative return path to the substation, in addition to other well-known benefits.

The rail configuration at special trackwork, turnouts, sharp curves, or crossovers may require jointed rails. Jumper cables, exothermically welded to the rail on either side of the bolted rail joint connections, ensure a continuous electrical path across the mechanical connections. Jumper cables may be used to bypass complex special trackwork to provide continuity. Jumpers can also protect track maintenance workers from electrical shock when they are replacing special trackwork components. The use of jumpers must be carefully coordinated with the design of the signal system .

8.3.2 Crossties

8.3.2.1 Concrete Crossties

Concrete crossties with an insulating base consisting of a rail pad and clip insulators provide good rail insulation. The rail seat pad is generally constructed of thermo-plastic rubber, ethylvinyl acetate, or natural rubber. It is approximately 6 to 16 millimeters (0.25 to 0.62 inches) thick and is formed to fit around the iron shoulder embedded in the concrete crosstie. The clip insulator may be a glass reinforced nylon material formed to sit on the rail and under the steel anchoring clip. This affords electrical insulation between the rail and the concrete tie anchoring clip. Insulating the rail base is important because concrete crossties, with their reinforcing steel, are not good insulators.

8.3.2.2 Timber Crossties

While wood is generally a good insulating material, timber crossties are only marginal insulators when they are treated with preservative chemicals or as they age and absorb moisture. While they provide sufficient insulation against low-voltage, low-amperage signal system currents, they also offer a leakage path for high-voltage, high-amperage traction power current. Timber crossties with insulating components at the fastening plate, as shown in Chapter 5 (Figure 5.4.2), can be used on main line track and at special trackwork turnouts and crossovers to reduce leakage.

Electrical insulation can be achieved by inserting a polyethylene pad between the metal rail plate and the timber tie, installing an insulating collar thimble to electrically isolate the steel plate from the anchoring lag screw, and applying coal tar epoxy to the hole for the lag screw. The insulating pad and collar thimble afford insulation directly between the two materials. Coal tar epoxy applied to the drilled tie hole fills any void between the end of the collar thimble and timber tie and affords some insulation between the lag screw and wood tie. The insulated tie plate pad should extend a minimum of 12 millimeters (0.5 inches) beyond the tie plate edges to afford a higher resistance path for surface tracking of stray currents. Chemical compatibility between the pad and epoxy material must be verified during design.

Maintenance shop tracks are grounded to protect workers. Maintenance yard tracks are generally floating or non-grounded, and insulation is rarely included between the rails and the timber crossties. This design decision is based on economic considerations, as well as the fact that the rails are only used sporadically and a separate traction power substation is used to supply operating current for train movement in the yard. The only time the yard rails become electrically connected to the main line or shop rails is when a train enters or leaves the yard or shop. This is a short period and does not result in any harmful sustained current leaking into the earth. Note that transit system structures within a yard complex may have to be protected against locally originated stray currents between yard trackage and the yard substation. Consequently, underground utilities in yards are constructed with non-metallic materials such as PVC, FRE, and polyethylene.

8.3.3 Ballast

To eliminate the path for stray current leakage from rail to ballast, the ballast section should be a minimum of 25 millimeters (1 inch) below the bottom of the rails. The clearance requirement pertains to rail on both concrete and timber crossties for both main line and yard trackage. This is essential to increase the rail-to-earth resistance and assist in minimizing the stray current leakage to earth. Ballast should be clean and well-drained. The use of metallic slags as ballast is not recommended. Rail grinding should be done with vacuum systems to minimize contaminating ballast with metallic grindings.

8.3.4 Embedded Track

Embedded track is generally located in the central business district (CBD) street-running section of a light rail system. Electrical isolation of the rails can be provided by insulating the rail face and rail base, insulating the trough that the rail sits in, or a combination of both. Track may also be isolated by insulating the perimeter of the entire concrete base slab, using the "bathtub" stray current isolation concept. The materials used to provide this insulation generally consist of polyethylene sheeting, epoxy coal tar coating, polyurethane grout (Icosit), or natural rubber sheeting, such as pads or rail boots. All these materials have been used successfully. The specific design for stray current control is selected by the track designer with recommendations from the corrosion control specialists.

8.3.5 Cross Bonds

Periodic cross bonding of the rails and parallel tracks provides equivalent rail-to-earth potentials for all rails along the system. Using all parallel rails to return current provides a lower negative return resistance to the substation, since the return circuit consists of multiple paths rather than individual rails.

Cross bonds are generally installed at impedance bond locations on rails to avoid interference with rail signal circuitry. Cross bonding is accomplished by exothermically welding insulated cables to the rails. Both rails are connected in single-track locations, with all four rails cross bonded in double-track areas.

Cross bonding in embedded track sections requires an alternative design approach since the signaling system is not carried through the embedded track area. This is typically the case as most embedded track light rail systems run on "line-of-sight" operating rules coordinated with street traffic signal patterns.

To provide cross bonding of embedded tracks, insulated conduits are generally installed between track rail troughs prior to installation of the concrete for the initial track slab. Insulated cables are exothermically welded to each rail to obtain electrical continuity. Smaller cables may be used to provide an easier turning radius to the rails in the rail trough zone and facilitate exothermic welding of the cables to the rails in constrained spaces. It is common design practice to install the cables at 305-meter (1,000-foot) intervals throughout the CBD, with one location being directly adjacent to each substation.

8.3.6 Direct Fixation Track

Direct fixation (DF) track is generally located on aerial sections or in tunnels in light rail transit systems. The direct fixation fasteners provide electrical insulation between the rails and the concrete structure. The elastomer design consists of a component of natural rubber bonded between the metal base plate and the top surface metal plate. An elastomer of the proper resistivity provides excellent insulation and deters current leakage. Fastener inserts are often epoxy coated to further isolate the rails from the concrete slab. Leakage may occur in DF track in tunnels that are subject to seepage. This coats the fastener with a wet conductive film, which can be mitigated by periodic cleaning.

8.3.7 Impedance Bonds

Leakage of stray currents into the earth can be a significant problem if the cables from the rails are electrically connected to an impedance bond housing case that is in contact with the earth. This type of grounded installation can result in a continuous maintenance problem if an effectively high rail-to-earth resistance is to be achieved. Instead, the housing case should be mounted clear of any concrete slab conduits, reinforcing bar and contact with the earth.

Impedance bond housing cases for a light rail transit line are generally located at-grade along the right-of-way. The cases are mounted on timber tie supports in the ballasted area either between or directly adjacent to the rails. In order to eliminate possible points of contact with the earth, the center taps of the impedance bonds are insulated from the mounting case by installing a clear adhesive silicone sealant between the center taps and the case.

8.3.8 Rigid Bumping Post

In order to reduce the frequency of maintenance required and maintain a higher degree of rail-to-earth resistance, rail insulating joints are installed in the rails to isolate the bumping post. The insulating joints eliminate the electrical connection between the bumping posts and the running rails and prevent leakage of stray currents into the earth.

Most of the methods discussed above (Sections 8.3.2 through 8.3.8) provide good initial values of rail-to-earth resistance. As these components deteriorate, they become dirty and require maintenance to maintain their original resistivity. Periodic tests are also required to locate and remove direct shorts that occasionally occur as discussed in the following section. Stray currents can rise to harmful levels if short circuits to ground are not detected and removed.

8.3.9 Stray Current Tests and Procedures

Regularly scheduled tests are required to maintain the integrity of stray current control systems once they are in operation. The most common tests are rail-to-earth resistance tests, substation-to-earth voltage tests, and structure-to-earth tests. Research shows a broad spectrum of approaches are used ranging from infrequent use of consultants to permanent in-house corrosion control personnel. The greatest efforts seem to be put forth when stray current problems have already damaged piping, utility structures, trackwork components, or signal circuits. Such troubleshooting can be effective, but conducting regularly scheduled, routine monitoring for stray currents problems can allow detection and correction before they manifest themselves in the form of measurable corrosion or degraded signal system performance.

8.4 SUMMARY

Corrosion from stray electrical currents is an important issue that requires the attention of the design team. There are several effective methods that have been used by the light rail system operators and builders to either avoid or mitigate the effects of stray current corrosion. The designer must seek the advice of experts in this complex field, as well as coordinate with the utility companies and the signal system designer. It is also important to recognize that track component specifications should include appropriate electrical resistance features to accomplish the corrosion protection plan. If such specifications are provided, the designer should not specify performance requirements for earth-to-ground resistance of the entire track system.

8.5 REFERENCES

[1] Fontana, Mars G. Corrosion Engineering, McGraw-Hill Book Company, Third Edition, Fontana Corrosion Center, Ohio State University 1988.

[2] Sidoriak, William & McCaffrey Kevin, *Source Control for Stray Current Mitigation*, APTA Rapid Transit Conference 1992, Los Angeles, California, June 1992.

[3] Moody, Kenneth J., *A Cookbook for Transit System Stray Current Control*, NACE Corrosion 93, paper No 14, New Orleans, Louisiana, February 1993.

[4] NACE International, "*Stray Current Corrosion: The Past, Present, and Future of Rail Transit Systems*," NACE International Handbook, Houston, Texas, 1994.

Chapter 9—Noise and Vibration Control

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CHAPTER 9: NOISE AND VIBRATION CONTROL

9.1. INTRODUCTION

Noise and vibration can cause significant adverse environmental impacts on wayside communities and, as a result, noise and vibration impact mitigation must be considered in track design. With appropriate design and maintenance provisions, noise and vibration from light rail transit can usually be held to acceptable levels at reasonable cost. Effective noise control must consider the vehicle and track as a system rather than as separate, independent components. For example, expensive track vibration isolation systems might be avoided where vehicles with low primary suspension vertical stiffness are used, whereas vehicles with high primary suspension stiffness might produce vibration that can only be controlled by a floating slab track—an expensive proposition. The track and vehicle design teams must coordinate their designs in the early stages of any project. Mitigation could involve considerable expense, weight, space, or special procurements Late consideration of noise and vibration isolation may preclude some treatments simply because insufficient time exists to obtain them or to implement design changes.

Many studies of rail transportation noise and vibration have been conducted, producing detailed technical reports containing comprehensive information concerning rail transit noise and vibration prediction and control. Particularly useful sources of literature include:

- The proceedings of the International Workshop on Railway and Tracked Transit System Noise (IWRN), which are usually published in the *Journal of Sound and Vibration*.[1]
- A review of the state-of-the-art in wheel/rail noise control has been prepared in Transit Cooperative Research Program (TCRP) Report 23, which includes numerous references to technical reports and other literature.[2]
- A review of groundborne noise and vibration prediction and control was performed in 1980, including preparation of an annotated bibliography [3]
- A handbook on all aspects of rail transit noise and vibration control has also been prepared.[4]

9.1.1 Acoustics

Sound in the form of noise is often included among the most significant negative environmental effects of new transit systems. The impact of noise will increase with tightness of track curvature, operation in city centers, speed, and other general track and operating conditions, unless noise and vibration control provisions are implemented in the track and vehicle designs.

Wayside noise primarily originates at the wheel/rail interface. During the passage of a train, the surface roughness of both the wheels and rails combined at the point of rolling contact (the contact patch) generates vibration in the rails, crossties, supporting track structure, wheels, and other vehicle components. These vibrating surfaces radiate sound to a greater or lesser extent, depending on the magnitude of vibration and the radiation or sending efficiency of the component. This is an area of active research in the European community, though primarily with respect to high-speed rail. The physics of noise and vibration generation and transmission for transit systems is similar or identical to that of high-speed rail.

Noise or sound pressure is conventionally described with a logarithmic decibel scale (dB). An approximation of the response of the human ear can be imposed on this scale by applying the 'A' frequency weighting network, which results in the A-weighted sound level (dBA).

The wheels and rails radiate approximately equal amounts of sound energy to the wayside or surrounding areas. The nature of sound is such that halving a sound energy emission produces only a 3-dB reduction in noise level, a difference that may be barely perceptible if frequency characteristics remain unchanged. This condition would be equal to no sound energy transmitted by the wheels while leaving the rails untreated, or vice versa. Therefore, noise control techniques have to be applied to both components to achieve a satisfactory reduction in sound level.

9.1.2 Scope

The purpose of this chapter is to provide guidelines with respect to track design for acceptable levels of noise and vibration. While many of the treatments considered here can be designed by the transit track engineer, the design of specific noise and vibration treatments, such as floating slabs, should be conducted by those who have considerable experience with designing and specifying vibration isolation systems. The noise and vibration designer should have an engineering or physics background and understand basic concepts in noise and vibration control.

The design of vehicle "on-board" and wayside treatments such as sound barriers are not included here, as these are beyond the limits of track design.

The following sections include guidelines for criteria on noise and vibration control at both the track wayside and vehicle interior, wheel/rail rolling noise, and wheel squeal. Rolling noise and wheel squeal are fundamentally different processes, hence their separation The final section concerns groundborne noise and vibration.

9.2. NOISE AND VIBRATION CONTROL DESIGN GUIDELINES

Guidelines have been developed by the Federal Transit Administration (FTA) and the American Public Transit Association (APTA). These standards or guidelines can be used as criteria for both airborne and groundborne noise in a transit corridor. The APTA guidelines recommend limits on maximum passby noise levels (i.e. the maximum noise levels that occur during an individual vehicle or train passby), as well as limits on the noise caused by ancillary facilities (i.e., fixed services associated with the transit system). The FTA guidance manual provides criteria for environmental impact analysis and mitigation in terms of the day-night level (L_{dn}) for both pre- and post-build conditions.[5] The FTA guidelines integrate the noise impact analysis for rail operations with that for other modes of transportation, such as highway or aircraft. The FTA guidance manual should be used to assess impacts for federally funded projects, and is recommended by the FTA for all rail transit projects. Refer to the FTA guidance manual for detailed description of the standards. For most practical situations, the wayside noise levels resulting from applying the FTA and APTA guidelines are very similar, though not identical.

The APTA guidelines are discussed below, because they may be used immediately by the track designer without detailed knowledge of existing ambient noise levels. The APTA guidelines pertain to standards that are typically adopted by transit agencies for the design of new rail facilities to determine the location and extent of mitigation measures necessary to avoid noise impacts. The design goals can be used directly without any assumptions regarding schedule, total number of trains or pre-existing ambient noise, as would be required when criteria are stated in terms of a noise exposure level metric. This results in a consistent design with similar mitigation being installed in areas with similar land uses or occupancies.

The various track structure types—ballast track, direct fixation track and embedded track—must be considered in meeting the criteria as each track type responds differently to wheel passage, and potential noise and vibration issues must be considered during the initial planning stages. The services of a recognized noise, vibration and acoustical expert in this field are recommended.

The APTA guidelines as listed in **Table 9.1** apply to different types of communities along the transit alignment as follows:

I Low-density urban residential, open space park, suburban residential, or quiet recreational areas with no nearby highways or boulevards.

II Average urban residential, quiet apartments and hotels, open space, suburban residential or occupied outdoor areas near busy streets.

III High-density urban residential, average semi-residential/commercial areas, parks, museums, and non-commercial public building areas.

IV Commercial areas with office buildings, retail stores, etc., with primarily daytime occupancy; central business districts.

V Industrial areas or freeway/highway corridors

The guidelines in Table 9.1 indicate maximum noise emissions from trains applicable to the land uses and types of buildings and occupancies along the transit route. The maximum passby noise level is the level in decibels relative to 20 micro-Pascal of the average root-mean-square (RMS) A-weighted sound pressure amplitude occurring during a train passby, usually for a 1- to 4-second average period.

This is not to be confused with the single-event noise exposure level (SENEL). Specific criteria are provided for various building types in the APTA guidelines.

The guidelines in **Table 9.2** indicate criteria for transit system ancillary facilities. Transient noise criteria apply to short duration events such as train passby noise transmitted through tunnel vent shaft openings.

Table 9.1
Criteria for Maximum Airborne Noise from Train Operations*

		Maximum Single Event Noise Levels (dBA)		
Category	Community Area	Single-Family Dwellings	Multi-Family Buildings	Hotels and Motels
I	Low-Density Residential	70	75	80
II	Average Residential	75	75	80
III	High-Density Residential	75	80	85
IV	Commercial	80	80	85
V	Industrial/Highway	80	85	85

* These criteria are generally applicable at the near side of the nearest dwelling or occupied building under consideration or 50 feet from the track centerline, whichever is furthest from the track center.

Source. "Guidelines and Principles for Design of Rapid Transit Facilities; Noise and Vibration," APTA 1979

Continuous noise design criteria apply to noises such as fans, cooling towers, and other long duration or stationary noises, except electrical transformers or substation facilities

For transformers and substation facilities (i.e., noise with tonal quality) the design criteria should be lowered by 5 dBA from the values in Table 9.2.

9.2.1 Groundborne Noise and Vibration Criteria

Guidelines are presented below for groundborne vibration impacts in buildings. The guidelines use the RMS vibration velocity level in dBV relative to 1 micro-inch/second as the principal descriptor of vibration impacts on building occupants. The RMS vibration velocity metric is incorporated in various standards and specifications.[6,7] Vibration prediction procedures are described in the FTA guidance manual and other literature.

The FTA guidance manual recommends criteria for wayside overall vibration velocity. These criteria are presented in **Table 9.3**

The environmental impact criteria recommended by the FTA for ground vibration are similar to American National Standards Institute (ANSI) standards for vibration in buildings.[8] The ANSI standard gives a baseline criterion curve for 1/3 octave band RMS vibration velocity of 100 micro-meters/second (4,000 micro-inches/ second), corresponding to a vibration velocity level of 72 dBV re 1 micro-inch/second. Where 1/3 octave analyses are not performed, the standard recommends a limit of 72 dB re 1 micro-inch/second for a frequency weighting that approximates the criterion curve for 1/3 octave levels. This latter limit is very similar to the vibration impact criterion of 72 dBV recommended by the FTA for floor vibration velocity levels in residences. For rail transit ground vibration, there is no practical difference between the weighted vibration velocity described in ANSI standard S3.29 and the overall, or unweighted, vibration velocity level, because most of the vibration energy occurs at frequencies above 8 Hz.

The vibration should be measured as the RMS vibration velocity occurring during vehicle consist passage. Thus, if a vehicle consist requires 4 seconds to pass, the RMS

Table 9.2
Guidelines for Noise from Transit System Ancillary Facilities*

Category	Community Area	Maximum Noise Level Design Criterion (dBA)	
		Transient Noises	Continuous Noises
I	Low-Density Residential	50	40
II	Average Residential	55	45
III	High-Density Residential	60	50
IV	Commercial	65	55
V	Industrial/Highway	70	65

* The design goal noise levels should be applied at 50 feet from the shaft outlet or other ancillary facility or should be applied at the setback line of the nearest line of the nearest buildings or occupied area, whichever is closer. For transformers or substation noise, reduce "Continuous Noises" by 5 dB.

Table 9.3
Groundborne Vibration and Noise Impact Criteria

Land Use Category	Groundborne Vibration Impact Levels (dBV re 1 micro-inch/second)		Groundborne Noise Impact Levels (dBA re 20 micro-Pascal)	
	Frequent Events[1]	Infrequent Events[2]	Frequent Events[1]	Infrequent Events[2]
Category 1: Buildings where low ambient vibration is essential for interior operations	65[3]	65[3]	NA[4]	NA[4]
Category 2: Residences and buildings where people normally sleep	72	80	35	43
Category 3: Institutional land uses with primarily daytime use	75	83	40	48

Notes:

1 "Frequent Events" is defined as more than 70 vibration events per day.

2 "Infrequent Events" is defined as fewer than 70 vibration events per day

3 This criterion limit is based on levels that are acceptable for most moderately sensitive equipment such as optical microscopes Vibration-sensitive manufacturing or research will require detailed evaluation to define the acceptable vibration levels.

4 Vibration-sensitive equipment is not sensitive to groundborne noise.

Source: *Transit Noise and Vibration Impact Assessment*, Federal Transit Administration, USDOT, April 1995

vibration should be measured over a duration approximately equal to 4 seconds. (The actual duration will depend on the integration times available from the analyzer.) The result obtained for the maximum vibration using a vibration meter with a slow response, equivalent to a 1-second averaging time, would be slightly higher than that obtained over the train passby duration by a fraction of a decibel at distances greater than about 15 meters (50 feet) from the track, and should be acceptable. A "fast" meter response, or integrating time shorter than 1 second, should not be used, because the vibration level may fluctuate considerably during vehicle passage, giving an unrepresentative reading. Fluctuation of vibration amplitudes and levels is a normal result of the random nature of low frequency ground vibration.

Typical design criteria for floor vibration are listed in **Table 9.4**, for the land use categories identified in the APTA Guidelines. These design criteria are not part of the APTA Guidelines, but have been applied to several transit systems, both heavy rail and light rail, in the United States. They are very similar to the FTA criteria described above. The guidelines for maximum groundborne vibration are presented in terms of dBV relative to 1.0 micro-inch/second.

Groundborne vibration that complies with these design criteria would not be imperceptible in all cases. However, the level would be sufficiently low so that no significant intrusion or annoyance should occur. In most cases, there would be vibration from street traffic, other occupants of a building, or other sources that would create vibration that is

Table 9.4
Criteria for Maximum Groundborne Vibration from Train Operations by Land-Use Category*

Category	Community Area	Maximum Single Event Groundborne Velocity Level (dBV re 10^{-6} in/sec)		
		Single Family Dwellings	Multi-Family Buildings	Hotels and Motels
I	Low Density Residential	70	70	70
II	Average Residential	70	70	75
III	High Density Residential	70	75	75
IV	Commercial	70	75	75
V	Industrial/Highway	75	75	75

* Criteria apply to the vertical vibration of floor surfaces within buildings.

equivalent to or greater than vibration from transit train passbys.

The APTA guidelines recommend limits on groundborne noise transmitted into building structures (see **Table 9.5**). They have been employed as design criteria for many heavy and light rail transit systems in the United States and are similar to the FTA criteria.

9.2.2 Wheel/Rail Rolling Noise

Rolling noise is associated with the action of the wheel rolling over tangent or curved track, and is produced primarily by rail and wheel surface roughness. Rolling noise is distinct from wheel squeal, which may occur at curves, both in nature and in generating mechanism. Rolling noise may be radiated by the wheels and rails, and may also be radiated by the structure supporting the track, such as elevated steel or concrete structures.

For the purpose of this chapter, wheel/rail noise is categorized into

- Normal rolling noise
- Impact noise due to loss of contact between the wheel and rail
- Rail corrugation noise
- Grinding artifact noise

Normal rolling noise is broadband noise produced by reasonably smooth rail and wheel treads. Departures from this "normal" condition include impact noise, corrugation noise, and grinding artifact noise. Impact and corrugation noise are more raucous and are usually the cause of community concerns about transit noise. While impact noise occurs at special trackwork, flat wheels, excessive rail roughness, undulation, corrugation, and rail joints also cause impact noise. Rail corrugation involves periodic rail roughness with wavelengths from 25 millimeters to 150 millimeters (1 to 6 inches), may be low amplitude, as during its initial stages, or may involve deep corrugation and contact separation. Grinding artifact noise is caused by a grinding pattern left in the rail by rail grinding machines, and has been confused with corrugation noise.

Table 9.5
Criteria for Maximum Groundborne Noise from Train Operations*

Category	Community Area	Maximum Single Event Noise Levels (dBA)		
		Single Family Dwellings	Multi-Family Buildings	Hotels and Motels
I	Low-Density Residential	30	35	40
II	Average Residential	35	40	45
III	High-Density Residential	35	40	45
IV	Commercial	40	45	50
V	Industrial/Highway	40	45	55

*Source: *Guidelines and Principles for Design of Rapid Transit Facilities, Noise and Vibration*, APTA 1979

9.2.2.1 Normal Rolling Noise

9.2.2.1.1 Generating Mechanisms

The following generating mechanisms have been identified as sources of normal rolling noise:

- Wheel and rail roughness
- Parameter variation of rail head geometry or moduli
- Dynamic creep
- Aerodynamic noise

Wheel and Rail Roughness. Wheel and rail surface roughnesses are believed to be the most significant cause of wheel/rail noise. The greater the roughness amplitudes, the greater the wayside noise and vibration. Assuming that the contact stiffness is infinite, the rail and wheel would displace relative to each other by an amplitude equal to their combined roughness amplitudes. The ratio of rail motion relative to wheel motion at a specific frequency will depend on the dynamic characteristics of the rail and wheel.

At short wavelengths relative to the contact patch dimension, the surface roughness is attenuated by averaging the roughness across the contact patch in a direction parallel with the rail, an effect known as contact patch filtering. Thus, fine regular grinding or milling marks less than 1 or 2 millimeters wide, should not produce as much noise as longer wavelength components, unless the milling marks are non-uniform.

Increasing the conformity of the wheel and rail contact has been proposed as a noise reduction technique that takes advantage of uncorrelated roughnesses between various parallel paths along the rail in the longitudinal direction.[9] Significant noise reductions on the order of 3 to 5 dB are predicted for frequencies on the order of 500 Hz. However, excessive wheel/rail conformity due to wear has been identified as a cause of spin-creep corrugation, leading to increased noise.[10] Therefore, care should be exercised before increasing the conformity of wheel and rail profiles. Excessive wheel/rail conformity from wear (and false flanging) will result if wheel profile truing is not conducted frequently. Further, good low-noise performance has been obtained with 115RE rail with a 250-millimeter (10-inch) head radius and cylindrical wheels.

Parameter Variation. Parameter variation refers to the variation of rail and wheel steel moduli, rail support stiffness, and contact stiffness due to variation in rail head ball radius. The influence of fractional changes in Young's elastic modulus and of radius-of-curvature of the rail head as a function of wavelength necessary to generate wheel/rail noise equivalent to that generated by surface roughness are illustrated in **Figure 9.1**. The wavelength of greatest interest is 25 to 50 millimeters (1 to 2 inches), corresponding to a frequency of about 500 to 1,000 Hz for a vehicle speed of about 97 km/hr (60 mph). Over this range, a variation in modulus of 3 to 10% is required to produce the same noise as that produced by rail roughness.

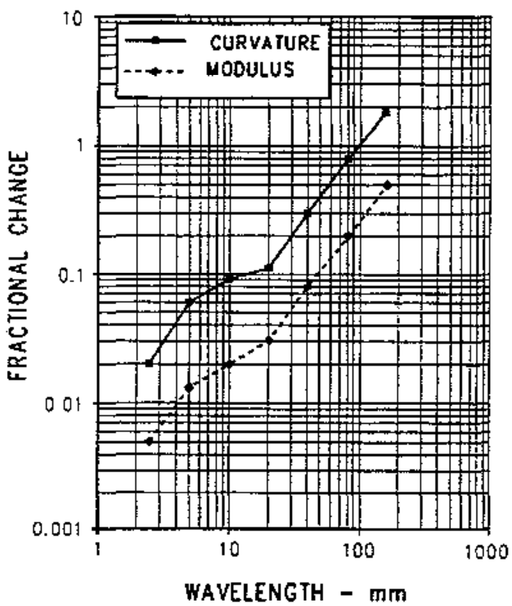

Figure 9.1 Change in Elastic Modulus and Rail Head Curvature Required to Generate Wheel/Rail Excitation Equivalent to Roughness Excitation

Rail head ball radius variation also induces a dynamic response in the wheel and rail. A variation of rail head curvature of the order of 10 to 50% produces noise levels similar to those produced by rail height variation alone. Rail head ball radius variation will normally accompany rail height variation. Maintaining a uniform rail head ball radius is necessary to realize the advantages of grinding rail to maintain uniform head height. Irregular definition of the contact wear strip is indicative of excessive ball radius variation. Thus, rail profile grinding with a vertical axis grinder to produce a distinct head curvature rather than simple grinding with a parallel axis grinder or block grinder is preferred.

Dynamic Creep. Dynamic creep may include both longitudinal and lateral dynamic creep, roll-slip parallel with the rail, and spin-creep of the wheel about a vertical axis normal to the wheel/rail contact area. *Longitudinal creep* is wheel creep in a direction parallel with the rail and is not considered significant by some researchers, who claim that rolling noise levels do not increase significantly during braking or acceleration on smooth ground rail. However, qualitative changes in wheel/rail noise on newly ground rail with an irregular transverse grinding pattern in the rail surface are audible as a train accelerates or decelerates, suggesting that longitudinal creep may play a role. *Lateral creep* is wheel slip across the rail running surface in a direction transverse to the rail during curve negotiation and is often accompanied by wheel squeal. Lateral creep may not be significant at tangent track, but may occur during unloading cycles at high frequencies on abnormally rough or corrugated rail, and may be responsible for short-pitch corrugation at tangent track. *Spin-creep* is caused by wheel taper that produces a rolling radius differential between the field and gauge sides of the contact patch. *Roll-slip* refers to rolling contact with slip at the edges of the contact zone. Some slip, continuous or otherwise, is required at the edges of the contact zone, as with Heathcote slip of a bearing in its groove, required by the conformal contact of curved contact surfaces.

Aerodynamic Noise. *Aerodynamic noise* due to high velocity air jets emanating from grinding grooves in the rail has been claimed to produce a high frequency whistling noise. No test data have been obtained to confirm this claim. It is further claimed that fine rail grinding removes course grinding marks and thus the noise. This is important if grinding is specified during construction to eliminate mill scale from the rail to obtain better traction and electrical conductivity. The grinding must have the fine quality mentioned previously and must maintain the design head radius for the rail.

Other sources of aerodynamic noise include air turbulence about the wheels and trucks, and traction motor blower noise. Neither of these is controllable by the track designer, but traction motor blower noise can, under certain circumstances, dominate the wayside noise spectrum if not properly treated. Aerodynamic noise due to air turbulence about the wheels and trucks at light rail transit speeds is not significant.

9.2.2.1.2 Wheel Dynamics

The dynamic response of the wheel has a substantial effect on rolling noise and vibration. The response is affected by axle bending modes beginning at about 80 or 90 Hz, tire resonances, spring-mass resonances of resilient wheels, and so forth. Up to about 400 Hz, the wheel is considered a rigid mass. At higher frequencies, these resonances cause a very complex response that is not easily described here.

9.2.2.1.3 Rail Dynamics

The dynamic response of the rail also influences the radiation of noise. Up to about 500 Hz, the rail behaves as a simple beam on an elastic foundation. At higher frequencies, standing waves may occur in the rail due to resonance between the rail supports. The first of these is the pinned-pinned mode of rail vibration. Estimates of the pinned-pinned mode resonance frequencies based on Timoshenko beam theory are presented in **Figure 9.2**. The pinned-pinned mode resonance frequencies of a rail supported at 900- and 750-millimeter (36- and 30-inch) spacing are about 500 Hz and 800 Hz, respectively. It has not been determined if the pinned-pinned mode is directly responsible for peaks in the wayside noise spectrum, but it is expected to have a bearing on wayside noise and possibly rail corrugation.

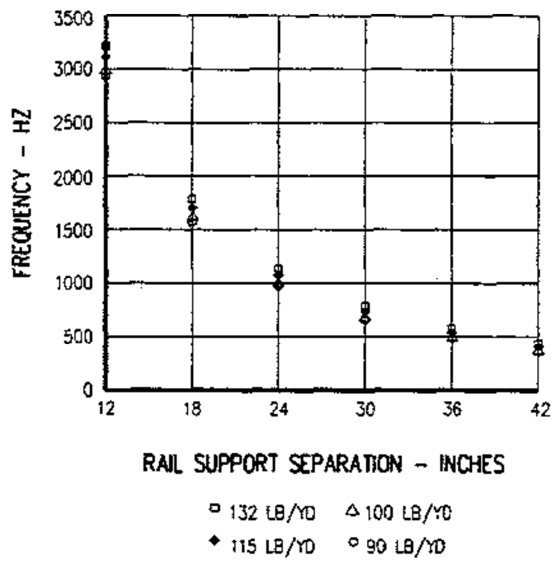

Figure 9.2 Vertical Pinned-Pinned Resonance Frequency vs. Rail Support Separation for Various Rails

Bending waves will propagate in the rail up to a frequency corresponding to 1/2 the pinned-pinned mode frequency in the case of rigid rail supports. Between this frequency and the pinned-pinned mode frequency, vibration transmissions along the rail may be attenuated, depending on the rail support dynamic characteristics, producing what is termed a "stop band." Between the pinned-pinned mode frequency and another cutoff frequency, bending waves may propagate freely, resulting in a "pass band." The response of the rail and its ability to radiate noise will be affected by the widths of the stop and pass bands. A slight randomness in the support separation may significantly alter the stop and pass band characteristics. Shortening the rail support pitch will increase the stop band frequency range, and thus reduce noise. Thus, 600 millimeter (24 inch) spacing is probably preferable to 750- or 900-millimeter (30-or 36-inch) spacing.

The main point here is that the response of the wheel and rail above 500 Hz is very complicated, and that the propensity for adverse interaction between these elements, leading to tonal components of wayside noise and possibly corrugation, is high. Track design should, ideally, be directed toward minimizing this possible interaction by ensuring that the pinned-pinned mode frequency is not coincident with an anti-resonance or resonance of the wheel. Reducing rail support spacing and introducing damping into the track support system may be useful for this purpose.

9.2.2.1.4 Resilient Direct Fixation Fasteners

Resilient direct fixation fasteners are used for rail support and provide modest vibration isolation. The most common form of resilient direct fixation fastener consists of top and bottom steel plates bonded to an elastomer pad. Modern designs incorporate anchor bolts that engage the bottom plate, so that the top plate is retained entirely by the elastomer vulcanized bond. The top plate contains recesses to retain the rail clips.

A direct fixation fastener is a complex mechanical element, even when considering only vertical motion. There are two frequencies that affect performance. One is the top plate resonating on the elastomer pad in rigid body motion and the other is the bending resonance of the top plate. The first of these can be thought of as a single-degree-of-freedom oscillator with mass equal to the top plate mass and spring equal to the top plate stiffness, and may occur at frequencies as low as 250 Hz. The second is influenced by the vertical stiffness per unit area of the elastomer and the bending stiffness of the top plate, and occurs at frequencies on the order of 650 Hz and higher. The fastener behaves as a pure spring below the single-degree-of-freedom resonance frequency. At higher frequencies, top plate bending amplifies the transmission of forces to the invert and produces a high reaction to rail motion that tends to "pin" the rail at this frequency, possibly interacting with the "pinned-pinned" mode. At higher frequencies the transmitted force declines significantly.

As with the pinned-pinned mode, the significance of fastener top plate bending on rail radiated wayside noise has not been determined. However, from the standpoint of track design, introduction of damping into the system and exploiting the top plate resonance may be beneficial. This would be achieved by incorporating a neoprene elastomer with high loss factor and tuning the top plate resonance to absorb vibration energy at the pinned-pinned mode frequency. Tuning the plate can be accomplished by changing the thickness. More research and testing are required to determine which approach is best.

9.2.2.1.5 Contact Stiffness

Contact stiffness is the ratio of the contact vertical force to the relative vertical deflection of the wheel and rail running surface. If the contact stiffness is small relative to the stiffness of the wheel or rail, wheel/rail forces will be controlled partially by the contact stiffness, in which case both the wheel and rail vibration will decrease in response to roughness. The contact stiffness does not vary greatly over the range of rail head ball radii. The ball contact stiffness varies about 16% for radii between 150 millimeters (6 inches) and 375 millimeters (15 inches). Under the most optimistic scenario, this variation would increase contact forces, and thus noise, by at most 1.5 dB. However, contact stresses may also increase as a result of a smaller contact area, and rail head geometry should be designed to minimize stress and wear. Also, some investigators have identified that high wheel/rail conformity with spin-slip corrugation and large ball radii may promote conformity. Corrugation notwithstanding, rail wear is not considered a serious problem at tangent track due to low transit wheel loads. Wheel tread concavity due to wear increases the lateral contact patch dimension. Although the rail head radius may be optimized for noise control, wheel tread wear may frustrate maintaining a specific contact geometry unless a vigorous wheel truing program is in place.

9.2.2.2 Impact Noise

Impact noise is a special type of wheel/rail noise occurring on tangent track with high amplitude roughness, rail joints, rail defects, or other discontinuities in the rail running surface and wheel flats. Impact noise is probably the most apparent noise on older transit systems that do not practice regular rail grinding and wheel truing.

Remington[11] provides a summary of impact noise generation that involves non-linear wheel/rail interaction due to contact separation, and is closely related to impact noise generation theory at special trackwork. I. L. Ver[12] categorizes impact noise by type of rail irregularity, train direction, and speed.

Modern transit systems employing continuous welded rail will likely not be concerned with impact noise generated by rail joints, though impact noise will be generated by rough rail, wheel flats, turnout frogs, and crossover diamonds. Even with continuous welded rail, rail welds and insulating joints must be carefully formed to reduce impact noise generation. Further, rail joint maintenance is important on older systems employing jointed rail. All systems must be concerned with rail grinding and wheel truing to eliminate associated impact noise. Impact noise due to rough wheels and rails is probably the most significant and irritating noise on older transit systems where rail grinding and wheel truing are not practiced.

9.2.2.3 Rail Corrugation Noise

Rail corrugation is a series of longitudinal high and low points or a wave formed in the rail head surface. Rail corrugation causes excessive rolling noise of a particularly harsh character and very high sound level. The terms "roaring rail," "roar," "wheel howl" or "wheel/rail howl" describe noise produced by corrugated rail. If rail corrugation exists, the wayside noise level will be much higher than that of normal rolling noise, and the frequency spectrum will contain discrete frequency components and associated harmonics.

Rail corrugation is more difficult to control on rail transit systems than railroads because of the lower contact static loads and uniformity of transit vehicle types and speeds, which prevent randomization of wheel/rail force signatures. Thus, maintaining rail smoothness is probably more important for transit systems than heavy freight systems. Rail corrugation is the principal cause of excessive noise levels on many transit systems, and controlling rail corrugation is key to minimizing rail transit system noise. At present, the most effective means of controlling rail corrugation is rail grinding. Detailed discussions of rail corrugation noise are included in TCRP Report 23.[2]

9.2.2.4 Treatments for Rolling Noise Control

Continuous welded rail, rail grinding, fastener support spacing, rail vibration absorbers and dampers, and rail head hardfacing are track-oriented treatments for controlling rolling noise Rail grinding is included because it pertains to track maintenance. Even though rail grinding is usually the task of the transit system operator, the initial grind may be performed during track construction to remove mill scale from the rail for better traction and electrical conductivity. The grinding must have the fine quality mentioned previously, and must maintain the design or specified head radius for the rail.

9.2.2.4.1 Continuous Welded Rail

Rolling noise levels with properly ground continuous welded rail and trued wheels in good condition are the lowest that can be achieved without resorting to extraordinary noise control measures. There are no rail joints to produce impact noise, which can be clearly audible with moderately maintained track. Noise from jointed rail may be as much as 5 dB higher than from continuous welded rail. Continuous welded rail requires less maintenance than jointed rail, so that the benefits of low noise are more easily obtained.

9.2.2.4.2 Rail Grinding

Rail grinding combined with wheel truing is the most effective method for controlling wheel/rail noise and maintaining track in good working condition. With ground rail and trued wheels, wheel/rail noise levels at tangent ballasted track are comparable with the combined noise levels from traction motors, gears, and fans.

As a track designer, it is important to plan for maintenance activities that must be performed to keep the system working well. Rail grinding to control noise is one of these activities. Consideration should be given to where grinding equipment (as well as other track maintenance equipment) can be staged to access the system. Short track shutdowns for maintenance are the norm in the industry. Therefore it is important to have practical solutions to providing access to work equipment.

Some grinders may have difficulty negotiating curves in tunnels or may be unable to grind rail on very short radius curves. Adequate clearance must be included in track and system designs to accommodate rail grinding machines. Rail grinding can be performed only if there is adequate access to the track during non-revenue hours. Grinding time can be optimized by minimizing travel time to and from the grinder storage location and the treatment section. Pocket tracks capable of storing the grinder during revenue periods will minimize travel time.

Vertical axis grinders with special provision may be able to grind embedded girder rail. Using standard T-rail sections provides the greatest flexibility with respect to grinding, especially on embedded curves.

The optimal grinding procedure includes grinding the rail to achieve a head radius profile with a 12- to 16-millimeter (1/2- to 5/8-inch) contact zone. This should be achieved with grinding facets of about 2 millimeters (1/16 inch). Multiple head grinders reduce the grinding time necessary to produce the desired contour. Computer controlled grinders with various grinding profiles stored in memory can simplify setup and further increase grinding time. The gauge corner can be finished in a manner consistent with the wheel profile. Grinding car speeds should be as slow as possible to reduce the wavelength of grinding patterns to a minimum. However, the speed should not be so slow as to produce excessive heating of the rail.

Rail grinding should be performed at intervals short enough to avoid the development of rail corrugation. Periodic track inspections for corrugation growth and noise increase should be conducted to identify appropriate grinding intervals. A grinding interval equal to the exponential growth time of corrugation (time for corrugation to grow by 167%) gives a rough estimate of the optimum grinding interval. Varying the location of the contact zone is used by some systems to reduce rutting of the wheel tread, and thus reduce wear resulting in conformal contact and spin-slip.

9.2.2.4.3 Rail Support Spacing

Rail support stiffness and damping, fastener resonances, and fastener spacing all directly influence high-frequency vibration of the rail. One of the most common sources of noise is short-pitch rail corrugation. Modification of rail support parameters may offer an opportunity to influence and possibly control the formation of rail corrugation, which has been related to the pinned-pinned mode of rail vibration. The pinned-pinned mode is, in turn, controlled by fastener spacing. The pinned-pinned mode resonance frequency is on the order of 800 and 500 Hz for fastener spacing of 750 to 900 millimeters (30 and 36 inches), respectively. Reducing the fastener spacing to 600 millimeters (24 inches) would drive the pinned-pinned mode resonance frequency to above 1,000 Hz, possibly high enough to smooth-out short-pitch corrugation at the contact patch, and thus reduce the corrugation rates. A second concern with respect to rail fastener spacing is a "singing rail" phenomenon associated with regularly spaced (concrete) crossties, rail seat pads, and spring clips. The transmission of vibration along the rail is subject to certain stop bands and pass bands in the frequency domain, which are closely related to the pinned-pinned mode resonance. Very precise fastener spacing may contribute to singing rail and pinned-pinned modes, and a slight randomization of crossties or fastener spacing may be beneficial. Reduction of concrete crosstie spacing to 600 millimeters (24 inches) will also raise the pinned-pinned mode resonance frequency above the anti-resonance frequency of the Bochum tire wheel, thus placing the maximum driving frequency of the tire in the stop band region of the rail vibration transmission spectrum This design provision should be investigated further. A 600-millimeter (2-foot) rail support spacing is now being considered by one transit system overseas with high volume and strict noise control requirements.

9.2.2.4.4 Direct Fixation Fastener Design

Resilient rail fasteners are effective in controlling structure-radiated wheel/rail noise by providing vibration isolation between the rail and structure and eliminating looseness in the rail fixation. Resilient elastomeric fasteners significantly reduce wayside noise from steel elevated structures relative to levels for conventional timber tie and cut-spike track. Softening the fastener further produces a marginal reduction of A-weighted noise. The best performing fasteners would include those that had the lowest static and dynamic stiffness with a top plate bending resonance in excess of about 800 Hz.

Noise radiated by rail in resilient direct fixation track is usually greater than for ballasted track due to the high acoustic reflectivity of concrete plinths and inverts. The character of wayside noise from resilient direct fixation track also differs significantly from that produced at ballasted track, probably due to differing dynamic characteristics of the rail support and rail support separation, as well as the amount of trackbed sound absorption.

Soft natural rubber fasteners support efficient propagation of bending waves that radiate noise. Incorporation of damped elastomers may be desirable to absorb rail vibration energy, thus reducing noise radiation. An attractive elastomer for this purpose is neoprene, which has an added advantage of resistance to ozone and oils, and is common in track construction. However, neoprene should not be used where vibration isolation is required to control structure-radiated or groundborne noise radiation. Where vibration isolation is needed more than airborne noise control, such as on steel elevated structures or in subway tunnels, natural rubber is the preferred elastomer, providing a dynamic-to-static stiffness ratio of less than 1.4.

The load vs. deflection curve of the fastener should be reasonably linear within +/- 15% of the mean static stiffness over the load range to maintain its dynamic properties over the load range. Specifying this linearity in an unambiguous way is critical in the procurement process. The fastener should provide full 3-degree-of-freedom isolation. Fasteners with hard horizontal snubbers can exhibit high non-linearity and compromise the vibration isolation that might be otherwise achievable. Fasteners with elastomer in shear are some of the best performing fasteners in this regard.

The tendency today in direct fixation track design is to provide fasteners with stiffness on the order of 15 to 20 MN/m, utilizing natural rubber elastomers in addition to neoprene and other synthetics. As noted above, while natural rubber has desirable properties for vibration isolation, the low damping capacity of these materials may promote bending wave propagation and noise radiation by the rail.

For additional information on direct fixation rail fasteners refer to Section 5.4.3.

9.2.2.4.5 Trackbed Acoustical Absorption

Ballasted track is well known to produce about 5 dB less wayside noise than direct fixation track, due to the sound absorption provided by the ballast and differences in the track-support characteristics. Acoustically absorptive concrete and wood blocks placed very close to the track are claimed to provide a noise reduction of 3 dB when installed on direct fixation track, which is consistent with that obtained with ballasted track relative to direct fixation track. This treatment has not been implemented in the US to date.

9.2.2.4.6 Rail Vibration Absorbers

Rail vibration absorbers are resonant mechanical elements that are attached to the rail base to absorb vibration energy and thus reduce noise radiation by the rail. Rail vibration absorbers have been employed in Europe, but have received little attention within the United States. Rail vibration absorbers may be desirable at certain site-specific locations. However, the size of the absorber may require substantial clearance space beneath the rail. The absorbers are usually tuned to frequencies above about 1,000 Hz, while the maximum noise levels may occur at about 500 to 800 Hz. Absorbers tuned to 500 to 800 Hz may require more mass than those now being offered in Europe. Data provided by certain manufacturers indicate a reduction of about 3 to 5 dB in rail vibration at 1/3 octave band frequencies between 300 and 2,000 Hz for 111 km/hr trains on tangent track. Absorbers were mounted on each rail, one between each rail fastener. The mass of each absorber was 23 kilograms (50 pounds).

Absorbers utilizing an elastomer element and optimized for moderate to high temperatures may lose a portion of their effectiveness at low frequencies. The leaf vibration absorber might be susceptible to freezing in sub-freezing weather with snow.

Vibration absorbers may be impractical on ballasted track unless they can be positioned clear of the ballast to maintain electrical isolation. Further, the ballasted track with timber crossties and cut spikes may provide substantial energy absorption without vibration absorbers, so that the addition of the absorber may provide little additional noise reduction. The absorber is effective where the track exhibits little damping, such as at concrete crossties and on ballast systems with spring clips and resilient rail seat pads.

9.2.2.4.7 Wear-Resistant Hardfacing

"Hardfacing" is the weld application of a metal alloy inlay to the rail head. The procedure involves cutting or grinding a groove in the rail surface and welding a bead of the alloy into the groove. The Riflex welding technique has been used on a limited basis in the United States, primarily for wear reduction, but has been promoted in Europe since the early 1980s for rail corrugation control and wheel squeal. For additional information on Riflex welding, refer to Section 5.2.5 in this handbook.

9.2.2.4.8 Low Height Sound Barriers

Low height barriers placed very close to the rail have been explored in Europe for controlling wheel/rail noise, perhaps just outside the wheel's clearance envelope. In one case, an aerial structure has been designed to provide a trough in which the vehicle runs, blocking sound transmission to the wayside. Sound absorption is used to absorb sound energy before it escapes the wayside. The height of the barriers must be determined by careful analysis. A 1- to 2-inch thick glass fiber or mineral wool sound absorber with perforated protective cover should be incorporated on the rail side of the barrier. Adding sound absorption to the concrete slab surface of direct fixation track should be considered.

9.2.3 Special Trackwork Noise

Special trackwork includes switches, turnouts, and crossovers. The noise generated at special trackwork by wheels traversing frog gaps and related connections is a special case of impact noise discussed above. Special trackwork noise may be controlled by grinding the frog to provide as smooth a transition as possible for each wheel to pass from one side of the flangeway to the other. Special frogs, including movable point, swing nose, and spring frogs, have been developed to minimize impact forces by eliminating the fixed gap associated with the frog Because the frog gap, combined with poorly maintained wheels, contributes to the increase in noise when a train passes through a turnout, the use of special frogs to reduce special trackwork noise may be a practical noise control provision for many transit systems.

9.2.3.1 Frogs

Various frog designs have been used in transit installations: solid manganese, flange bearing, liftover, railbound manganese, spring, and movable point frogs. For additional information on frog design, refer to Section 6.6. The following guidelines are provided for frog design selection for noise control.

9.2.3.1.1 Solid Manganese Frog

Solid manganese frog design with welded toe and heel joints provides a virtually continuous running surface except for the open flangeway. Proper wheel and frog design along with continuous track maintenance and wheel truing should provide adequate low-noise operation. Hollow worn wheels with false flanges will contribute to noise and vibration when traversing through the frog.

9.2.3.1.2 Flange-Bearing Frog

Flange-bearing frog design with welded toe and heel joints is similar to the solid manganese design except the frog provides support to the wheel flange while traversing the flangeway opening frog point area. The depth of the flangeway is reduced to a limit to support the wheel in the point area. If the wheel and frog are properly maintained, this design reduces impact of the wheel in the open flangeway frog point area. Gradual ramping of the flangeway is critical to avoiding impact noise.

9.2.3.1.3 Liftover Frog

Liftover frog design with welded toe and heel joints is similar to the flange-bearing design except the frog provides a continuous main line running rail surface and open flangeway. The lateral move flangeway is omitted in this design.

When a movement occurs for the diverging route, the frog flangeway and wing rail portion is ramped up to a level that allows the wheel to pass over the main line open flangeway and running rail head. If the wheel and frog are properly maintained, this design eliminates impact on the main line moves and reduces impact of the wheel in the diverging direction.

The three frog designs described above are recommended for light rail transit installations to reduce noise and vibration. The frogs can be considered for three track types: ballasted, direct fixation and embedded special trackwork.

9.2.3.1.4 Railbound Manganese Frogs

Railbound manganese frogs with the running rail surrounding the central manganese portion of the frog introduce interface openings in the running rail surface in addition to the flangeway openings. Light rail main line track installations should always consider welded joints at the toe and heel of the frog. The manganese-to-rail-steel interface in the frog design introduces a joint in the running surface that severely impacts wheel performance and is the source of wheel batter noise and vibrations from the outset of installation They are not as quiet as the frogs described above.

9.2.3.1.5 Movable Point Frogs

Movable point frogs are perhaps the most effective way to eliminate the impact noise associated with fixed flangeway gap frogs. The frog flangeway is eliminated by laterally moving the nose of the frog in the direction in which the train is traveling. The movable point frog generally requires additional signaling, switch control circuits, and an additional switch machine to move the point of the frog. Movable point frogs have been incorporated on people mover systems in Canada and in Australia, but have received little or no application on light rail transit systems in the United States.

9.2.3.1.6 Spring Frogs

Spring frogs also eliminate the impact noise associated with fixed flangeway gap frogs for trains traversing the frog in a normal tangent direction. The spring frog includes a spring-loaded point, which maintains the continuity of the rail's running surface for normal tangent operations. For diverging movements, the normally closed frog is pushed open by the wheel flange. There may be additional noise associated with trains making diverging movements, because the train wheels must still pass through the fixed portion of the frog Thus, use of these frogs in noise-sensitive areas where a significant number of diverging movements will occur will not significantly mitigate the noise impacts associated with standard frogs.

9.2.4 Wheel Squeal Noise

Wheel squeal is one of the most serious types of noise produced by light rail transit systems and can occur at both short- and long-radius curves. In a central business district, pedestrians and patrons are in close proximity to embedded track curves of light rail systems; consequently, they are subjected to high levels of squeal noise. The high levels of noise at discrete squeal frequencies result in high perceptibility and annoyance

Wheel squeal may be intermittent, due to varying contact surface properties, surface contaminants, or curving dynamics of the vehicle and rail. On wet days, wheel squeal may be eliminated when negotiating all or most of a curve.

9.2.4.1 Causes of Wheel Squeal

Three assumed types of vibratory motion producing wheel squeal noise are:

1 Longitudinal slip with non-linear rotational oscillation of the tire about its axle
2 Wheel flange contact with the gauge face of the rail
3 Lateral slip with non-linear lateral oscillation of the tire across the rail head.

Longitudinal slip is due to the different translation velocities between the high and low rail wheels in a direction parallel with the rail. Longitudinal slip is expected on curves where the distance traversed at the high rail is greater than at the low rail. Wheel taper is sufficient to compensate for differential slip on curves with radii in excess of about 610 meters (2,000 feet), though shorter radii may be accommodated by profile grinding of the rail head and gauge widening. Further, Rudd reports that elastic compression of the inner wheel and extension of the outer wheel tread under torque can compensate for the wheel differential velocities, and, further, that trucks with independently driven wheels also squeal.[13] The consensus of opinion is that longitudinal slip is not a cause of wheel squeal.

Wheel flange rubbing is due to contact between the flange and high rail and occurs on short-radius curves with significant crabbing of the wheel set, such as at gauge widened curves However, lubrication of the flange does not entirely eliminate wheel squeal and wheel squeal is not limited to the high rail, suggesting that flange contact is not necessarily the only significant cause of squeal. Flange rubbing is also accompanied by lateral slip, which may be the primary cause of squeal.

Lateral slip with non-linear lateral oscillation of the tread running surface across the rail head is believed to be the principal source of squeal. **Figure 9.3** illustrates the geometry of curve negotiation by a transit vehicle truck. Lateral slip across the rail head is necessitated by the finite wheel base (B) of the truck and the radius of curvature of the rail, where no longitudinal flexibility exists in the axle suspension. However, **Figure 9.4** illustrates the actual crabbing of a truck. In this case, the leading axle of the truck rides towards the high rail, limited only by flange contact of the high rail wheel against the gauge face of the rail. The trailing axle travels between the high and low rail, and the low rail wheel flange may, in fact, be in contact with the low rail gauge face. Gauge widening, common on many transit systems, increases the actual creep angle (angle of attack) and exacerbates the generation of wheel squeal. For additional information on truck rotation refer to Section 4.2.9.

The friction between the wheel and rail running surfaces during lateral slip varies non-linearly with the lateral creep function, defined as the lateral relative slip velocity divided by the forward rolling velocity. The coefficient of friction initially increases with increasing creep function, reaching its maximum at a creep function of about 0.09, and declining thereafter. The negative slope results in negative damping that, if sufficient to

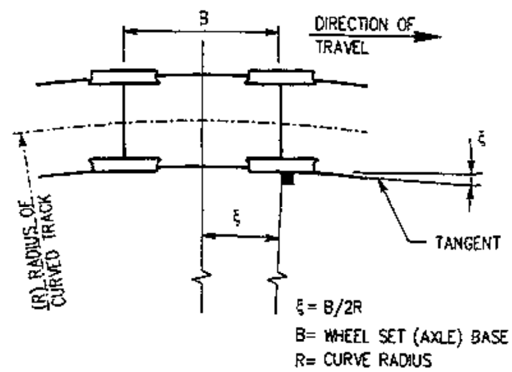

Figure 9.3 Geometry of Curve Negotiation and Lateral Slip

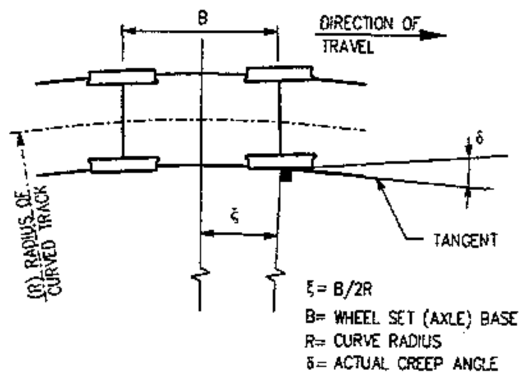

Figure 9.4 Truck Crabbing Under Actual Conditions

overcome the internal damping of the system, will produce regenerative oscillation or squeal.

For a wheel base of 2280 millimeters (7.5 feet), squeal would not be expected for curve radii greater than 125 to 253 meters (410 to 830 feet), the lower limit being achieved when there is no gauge widening. As illustrated above, gauge widening increases the creep angle for the same radius of curvature. A typical assumption is that squeal does not occur for curves with radii greater than about 200 meters (700 feet), corresponding to a dimensionless creep rate equal to 0.7 *B/R*, where *B* is the wheel base and *R* is the curve radius.

Meteorological conditions affect the generation of squeal. In wet weather, for example, wheel squeal is greatly reduced due to the change in friction characteristics caused by moisture. Wheel squeal may be naturally reduced in areas of high humidity.

9.2.4.2 Treatments

There are a number of mitigation measures available for controlling wheel squeal. The most effective of these are resilient and damped wheels. Resilient wheels are not a component of track design, but their use greatly reduces the need for track or wayside mitigation . Again, wheel squeal control is a system problem rather than simply a vehicle or track design problem. Other treatments may be considered for application directly to the track.

9.2.4.2.1 Dry-Stick Friction Modifiers

Modification of the friction-creep curve is an attractive approach to controlling wheel squeal. Dry-stick friction modifiers applied to the wheel tread, and thus the rail running surface, improve adhesion and flatten the friction-creep curve, thereby reducing or eliminating the negative damping effect. Friction modifiers are being offered as an on-board treatment for wheel squeal. The treatment has also been applied directly to the rail head with moderate success. Manual application of wayside friction modifiers can be considered for controlling squeal on curves, but no fixed automatic applicators are commercially available at this time.

9.2.4.2.2 Lubrication

Wayside lubricators can be used to lubricate the rail gauge face, restraining rail, and wheel flange. However, this leads to an undesirable situation; the lubrication tends to migrate to the running rail head, reducing wheel squeal due to lateral slip at the expense of loss of traction. The effectiveness of this type of lubrication in reducing noise can be substantial. Without lubrication, maximum wheel squeal noise levels may exceed 100 dBA. With lubrication, wheel squeal noise levels have been reduced by approximately 15 to 25 dB.

Wheel tread and rail running surfaces cannot be lubricated without loss of adhesion and braking effectiveness. Loss of braking effectiveness will result in wheel flatting, which produces excessive rolling noise, a counterproductive result of improper lubrication. Loss of wheel-to-rail electrical contact from the use of uncontrolled wayside lubricants is also a concern. Environmental degradation by lubricants is a serious consideration; thus lubricants should be biodegradable to the maximum extent possible.

9.2.4.2.3 *Water Sprays*

Water spray by wayside applicators on curved track can be used to control wheel squeal, rail corrugation and wear. Both the high and low rails can be treated. Water spray has been reported to reduce wheel squeal by 18 dB on short-radius curves. Water spray cannot be used during freezing weather. Water sprays may induce corrosion that is not conducive to electrical contact, and might not be advisable for lightly used track or where signaling may be affected. Water sprays would likely pose less of an environmental problem than grease or oil.

9.2.4.2.4 *Rail Head Inlays*

The friction versus creep curve can be modified by treatment of the rail heads with a babbit-like (soft malleable metal) material. This treatment has been successful in eliminating wheel squeal, reducing passby noise levels by approximately 20 dB. However, after several months of service, "chronic squeal reappeared." The loss of performance is likely due to wear of the material, allowing wheel tread contact with the native rail steel. Refer to Section 5.2.5 for additional information concerning rail head treatments.

9.2.4.2.5 *Rail Head Damping Inlays*

Rail head damping, consisting of a synthetic resin glued to a groove in the rail head, has been offered as a treatment to control wheel squeal. This procedure has been applied for at least a year on German rapid transit systems, and can be applied to all grades of steel. The vulcanization process is used with all types of rails and is applied so that the wheel does not come into contact with the resin-based filler material. The manufacturer claims that noise is reduced by the material damping provided by the resin inlay. No performance data have been provided and there are significant questions regarding actual performance, wear, and squeal noise reduction. This approach should be thoroughly checked and tested before applying it as a general noise reduction treatment.

9.2.4.2.6 *Track Gauge*

Gauge narrowing is an attractive approach to promoting curving and reducing crab angle and creep, and thus squeal. However, the wheel and rail gauges used on trolley systems typically vary by 3 millimeters (1/8 inch), and this slight variation in gauge may dictate against gauge narrowing in curves to prevent the flanges from binding when axle spacing is taken into consideration. Refer to Section 4.2 for additional information concerning track and wheel gauge.

Gauge widening has been incorporated in track design to control squeal and promote curving, but has produced the opposite effect. Gauge widening appears to be a holdover from steam locomotive days when locomotives with three-axle trucks were in use, and is not specifically necessary to prevent excessive flange wear for two-axle trucks. Quite the opposite; gauge widening promotes crabbing because the natural tendency of a truck is to crab its way through a curve, with the high rail wheel of the leading axle riding against the high rail, as illustrated in Figure 9.4.

9.2.4.2.7 Asymmetrical Rail Profile

Asymmetrical rail head profiles are designed to increase the wheel rolling radius differential and promote self-steering of the truck through the curve, which requires a longitudinally flexible truck. In this case, the contact zone of the high rail is moved toward the gauge corner and the larger diameter of the tapered wheel, while the contact zone at the low rail is moved to the field side and the smaller diameter of the taper. The wheel taper thus allows the high rail wheel to travel a greater distance than the low rail wheel per revolution. In so doing, the axles tend to line up with the curve radius, thus reducing the lateral slip squeal. While this approach is attractive, it is effective for curve radii of the order of 200 meters (700 feet) or more. This process has been used in Los Angeles and Vancouver.

9.2.4.2.8 Rail Vibration Dampers

A rail vibration damper is a visco-elastic constrained layer damping system applied to the rail web to retard wheel squeal. In one design, the constrained layer damper is held against the rail web with a steel plate and spring clip under and about the base of the rail. The treatment can be applied with minimal disturbance of track, provided that it may be made short enough to fit between the track supports. A second design includes a damping compound that is bonded to the rail web and constraining steel plate, without the use of a steel spring clip.

9.2.4.2.9 Rail Vibration Absorbers

Rail vibration absorbers are resonant mechanical elements that are attached to the rail to absorb vibration energy. Rail vibration absorbers are reputed to control wheel squeal and also reduce rolling noise. This technology has not been tried in the United States as of this writing. The most attractive design at present incorporates a series of tuned dampers that bear against both the rail foot and the rail web. Thus, vibration energy is absorbed from both these elements of the rail. The absorbers are clamped to the rail with bolts, and a plate extends beneath the base of the rail. These systems have been used in Europe, but not in North America.

9.2.4.2.10 Double Restrained Curves

Double restraining rails are designed to reduce the angle of attack and promote steering of the truck without flange contact on gauge widened curves. In this case, the high rail wheel flange can be brought away from the high rail by the low rail restraining rail and the low rail wheel flange can be moved away from the gauge face by the high rail restraining rail. The restraining rail flangeway width would have to be controlled to prevent binding of the wheel set or climbing of the flange onto the restraining rail. Further, the restraining rails may be liberally lubricated to reduce squeal and wear due to friction between the wheel and restraining rail. However, no successful installations have been found that completely eliminate wheel squeal. Although this approach is theoretically attractive in reducing crab angle, mixed results may be achieved. Curving may be promoted most by maintaining gauge through the curve or possibly narrowing the gauge. Refer to Section 4.2.8 for additional information concerning guarded track and restraining rail.

9.2.5 Groundborne Noise and Vibration Mitigation

Groundborne noise and vibration is a phenomenon of all rail transit systems and, if not controlled, can cause significant impact on residences, hospitals, concert halls, museums, recording studios, and other sensitive land uses. New light rail transit alignments include abandoned railroad rights-of-way passing through adjacent residential developments. Residences located within 1 meter (3 feet) of right-of-way limits are not uncommon, and there are instances where apartment buildings are built directly over light rail systems with little provision for vibration isolation. Vibration impacts on hospitals, sensitive "high-tech" manufacturers, or research facilities may occur.

Groundborne noise is heard as a low level rumble, and may adversely impact residences, hospitals, concert halls, and other areas or land uses where quiet is either desirable or required. Groundborne vibration in buildings may be felt as a low frequency floor motion, or detected as secondary noise such as rattling windows or dishes. Building owners often claim that groundborne vibration is responsible for building settlement and damage, though there have been no demonstrated cases of this occurring.

Literature concerning rail transit groundborne noise and vibration control is rich with empirical and quantitative studies conducted in North America, Europe, Australia, the Far East, and South America. A substantial review of the state-of-the-art in groundborne noise and vibration prediction and control was conducted in 1984 for the U.S. Department of Transportation. Recent research includes studies on the nature of subway/soil interaction, surface track vibration generation, and extensive downhole testing to assess vibration propagation in soils. Indeed, the task of predicting groundborne noise and vibration has advanced to a highly developed state, relying on downhole shear wave velocity data, seismic refraction data, borehole impulse testing, and detailed finite element modeling of structures and surrounding soils. As a result, vibration predictions can be reasonably accurate, though still less precise than noise predictions. Special track design is now regularly considered as a means to control perceptible ground vibration in addition to audible groundborne noise.

9.2.5.1 Vibration Generation

Ground vibration from rail transit vehicles is produced by wheel/rail interaction, driven by roughness in the wheels and rail running surfaces, discrete track structures, track irregularities, and imbalanced conditions of rotating components such as wheels and axles. Vibration forces are imparted to the track invert or soil surface through embedded track, direct fixation fasteners, or ballast. These forces cause the transit structure and soil to vibrate, radiating vibration energy away from the track in the form of body and surface waves. Body waves are shear and compression waves, with respective shear and compression wave propagation velocities. Body waves attenuate (or lose amplitude) at a rate of 6 dB (50% in amplitude) as distance from the source doubles without material damping (energy absorption) in the soil. Of these two wave forms, the shear wave is the most important. For surface track, the ground vibration includes Rayleigh surface waves, which attenuate at a rate of 3 dB (30% in amplitude) as distance from the source doubles without material damping or reflection losses. Rayleigh surface waves are the major carrier of vibration energy from the surface track, but inhomogeneities in the soil may convert significant portions of the Rayleigh surface wave energy into body waves. Within one wavelength of the track, the distinction between surface and body waves is immaterial, as near-field effects dominate the response.

Structure/soil interaction significantly affects the radiation of vibration energy into the surrounding soil. Heavy tunnel structures produce lower levels of ground vibration than lightweight tunnels. However, the opposite has been observed for large cut-and-cover box structures very close to the ground surface relative to circular tunnels. Near-surface subway structures produce vibration more easily than deep structures.

Ground vibration excites building foundations and structures. Vibrating surfaces of the rooms then radiate noise into the room as groundborne noise. The interior sound level is then controlled by the degree of acoustical absorption contained in the room. Secondary noise, such as rattling windows, might be observed in extreme cases.

9.2.5.2 Groundborne Noise and Vibration Prediction

The procedure for predicting groundborne noise and vibration is an empirical approach involving transfer function testing of soils and buildings. The procedure has recently been adopted by the FTA for use in assessing groundborne noise and vibration impacts by rail transit projects. The predictions of ground vibration and groundborne noise are described in detail in the FTA guidelines for rail transit noise and vibration impact assessment.[14] Screening procedures and detailed prediction techniques are also described.

The state-of-the-art in predicting ground vibration has recently advanced significantly to include detailed finite element modeling of soil/structure interaction[15], numerical analysis of vibration propagation in layered soils using both analytical and finite element modeling methods, and multiple-degree-of-freedom modeling of transit vehicles and track.[16] These methods are very powerful for analyzing changes in structure design, structure depth, and vehicle designs.

9.2.5.3 Vibration Control Provisions

Numerous methods for controlling groundborne noise and vibration include continuous floating slab track, resiliently supported two-block ties, ballast mats, resilient direct fixation fasteners, precision rail, alignment modification, low stiffness vehicle primary suspension systems, and transmission path modification.[17] Achieving the most practical solution at reasonable cost is of great importance in vibration mitigation design. Factors to consider include maintainability, inspectability, and cleanliness.

9.2.5.3.1 Floating Slab Track

Floating slab track is a special type of track structure that is beyond the normal designs discussed in Chapter 4. The floating slab concept would be an additional requirement to normal track structure. Track structure design must allow for floating slabs where they are needed, as the floating slab may require additional invert depth.

Floating slab systems consist of two basic types:

- Continuous cast-in-place floating slabs are constructed by placing a permanent sheet metal form on elastomer isolators and filling the form with concrete. The floating slabs measure approximately 6 meters (20 feet) along the track and 3 meters (10 feet) transverse to the track. The depth of the slab is generally 300 to 450 millimeters (12 to 18 inches).
- Discontinuous double-tie pre-cast floating slabs measure about 1.5 meters (5 feet)

along the track and 3 meters (10 feet) transverse to the track. The depth, and thus the mass, of the slab may vary from about 200 to 600 millimeters (8 to 24 inches). The mass of the slab may range from 2,000 to 7,000 kilograms (4,409 to 15,430 pounds.) The most common configuration is with a 2,000-kilogram (4,409-pound) slab 200 millimeters (8 inches) thick. The slabs are referred to as double ties because they support each rail with two direct fixation fasteners, giving a total of four direct fixation fasteners per slab.

The design resonance frequency of a floating slab system is the resonance frequency for the combined floating slab and vehicle truck mass distributed over the length of the vehicle. The design resonance frequency of the continuous floating slab and vehicle combination is typically on the order of 16 Hz, while that of the discontinuous pre-cast double-tie floating slab and vehicle combination ranges from 8 to 16 Hz, depending on isolation needs. With a continuous floating slab, the entrained air stiffness must be included with the isolator spring stiffness when computing the resonance frequency.

The normal configuration for the discrete double-tie design includes four natural rubber isolators. Additional isolators are incorporated to increase the isolation stiffness at transition regions between non-isolated and isolated track. The main support pad shape was selected to provide low shear strain and control lateral slip between the bearing surface of the pad and concrete surfaces. Lateral slip is further reduced by gluing the pads to the concrete surfaces. The pad is about 100 millimeters (4 inches) thick, with an overall diameter of 400 millimeters (16 inches).

The main support pads of all discontinuous floating slabs used in the United States are manufactured from natural rubber. Synthetic rubber formulations exhibit higher creep rates than natural rubber formulations and should be avoided. Natural rubber formulations exhibit low creep over time, high reliability, and dimensional stability. Natural rubber pads are not subject to corrosion and provide natural material damping that controls the amplification of vibration at resonance. Natural rubber pads installed beneath floating slabs have survived subway fires without needing to be replaced and their use results in a virtually maintenance-free isolation system. There have been concerns over debris accumulating beneath floating slabs, as well as providing methods for removal of such debris. Another concern is the possibility of the gaps between discontinuous floating slabs, which could trap the feet of persons escaping down a tunnel during an emergency. Both of these concerns may be avoided by providing flexible seals, but care must be taken to avoid increasing the overall stiffness of the floating slabs by using the seals.

9.2.5.3.2 Resiliently Supported Two-Block Ties

Resiliently supported two-block tie designs are referred to as encased direct fixation track in Section 4.5.3.4. In resiliently supported two-block tie designs, each rail is supported on individual concrete blocks set in an elastomer boot encased by the concrete slab or invert. A stiff elastomer or plastic rail seat pad protects the concrete block at the rail base, which is retained by a spring clip or other fastening system. The design used for light rail transit vibration isolation must provide a low rail support modulus, achieved by including a closed-cell elastomer foam (or micro-cellular pad) between the bottom of the concrete block and invert inside the elastomer boot. Static stiffnesses of the order of 8.9 to

17.8 MN/meter (50,000 to 100,000 pounds/inch) can be obtained, though the dynamic stiffness is likely to be much higher. The design constitutes a two-degree-of-freedom vibration isolation system, though the vibration isolation at low frequencies is controlled by the elastomer boot surrounding the concrete block.

The vibration isolation provided by resiliently supported two-block ties is believed to be higher than that of very stiff direct fixation fasteners. The vibration isolation provided by the two-block tie should be comparable to that provided by soft fasteners, with stiffness of 8.9 MN/meter (50,000 pounds/inch) and dynamic stiffness of 11 6 MN/meter (65,000 pounds/inch). Damping has been postulated as a cause for the low-frequency vibration isolation provided by some of the two-block systems. The two-degree-of-freedom isolation of the two-block system may provide greater vibration isolation at frequencies above 200 Hz than that provided by soft fasteners.

There have been cases of rail corrugation associated with the resiliently supported tie system, though this appears to be related to the interaction of the rail with the concrete block through the rail seat pad. Reducing the rail seat pad stiffness appears to defer the onset of rail corrugation.

9.2.5.3.3 Ballast Mats

Ballast mats are employed to control groundborne noise and vibration from ballasted track and have been incorporated as the principal isolator in certain floating slab track installations. The effectiveness of a ballast mat is limited to frequencies above approximately 25 to 30 Hz. The maximum vibration isolation that has been measured from trains with ballast mat is about 10 dB at 40 Hz. At lower frequencies, the ballast mat is too stiff to provide sufficient vibration reduction relative to standard ballasted track. The ballast mat is, therefore, not a substitute for floating slab track. There may be some amplification of vibration at the ballast mat resonance frequency in the range of 16 to 30 Hz.

Three configurations of ballast mats have recently been recommended for surface track. The first includes a concrete base with a mat consisting of inverted natural rubber cone springs placed on a concrete base beneath the ballast. The second includes the mat placed in a concrete "bath tub" slab with the track slab consisting of a second pour concrete slab supporting the rails. The third, and potentially less effective design, incorporates a uniform ballast mat placed directly on tamped soil or compacted sub-ballast.

Conventional installations of ballast mats in Europe have been in subways with concrete bases, for which vibration insertion losses have been predicted to be higher than observed in practice. Surface track application presents challenges that limit the effectiveness of ballast mat installations. The shear modulus of the soil at or near the surface may be low and can result in a support modulus comparable to that of the ballast mat, thus rendering the ballast mat less effective than if it were employed in tunnel track.

The vibration reductions are limited to the frequency range in excess of about 30 Hz. For ballast mats on compacted subgrade, the insertion loss would likely be on the order of 5 to 8 dB at 40 Hz. For ballast mats on a concrete base or concrete invert, the insertion loss at 40 Hz would be between 7 and 10 dB. The most effective ballast mat is a profiled mat with a natural rubber elastomer on a concrete base or trough. This type of installation provides the greatest vibration isolation, about 10 dB at 40 to 50 Hz.

The selection of a ballast mat should favor low static and dynamic stiffness, low creep, good drainage, and ease of installation. There are considerable disparities between the dynamic stiffnesses of various ballast mats, even though their static stiffnesses may be similar. The most desirable material is natural rubber, which exhibits a low dynamic-to-static stiffness ratio of about 1.4 or less. These high-performance natural rubber mats may cost more than synthetic elastomer mats, but may be the only choice in critically sensitive locations. Specifications for ballast mats should include dynamic stiffness requirements for the intended frequency range over which vibration isolation is desired. If this is not done, much less isolation than expected may actually be achieved, rendering the vibration isolation provision ineffective. There is a very distinct possibility that providing a ballast mat may increase low frequency vibration in the 16- to 25-Hz region. If this is the range of the most significant vibration, the ballast mat may actually create or exacerbate a vibration impact. Thus, great care must be exercised in design, specification, and installation of the ballast mat.

A further consideration is ballast pulverization and penetration into the mat. Ballast mats have been incorporated in the track structure to reduce pulverization.

9.2.5.3.4 Resilient Direct Fixation Fasteners

Resilient direct fixation fasteners are used for concrete slab aerial deck or subway invert track. In some instances, resilient direct fixation fasteners have been incorporated into embedded track. One of the earliest direct fixation fastener designs was the Toronto Transit Commission unbonded fastener with natural rubber pad. This relatively stiff fastener is now being replaced. Modern designs include vulcanize-bonded fasteners with rolled steel top and bottom plates. More recent designs include cast top plates and either rolled steel or cast base plates.

Very soft fasteners provide a modest measure of groundborne noise reduction. Certain fasteners use elastomer in shear to provide good rail head control. Soft fasteners have been designed for use in reducing ground vibration and groundborne noise at frequencies above about 30 Hz. The elastomer's shear design provides a vertical stiffness of about 10 MN/meter (55,000 pounds/inch). A unique aspect of this type of fastener is that it must pass a qualification test, which includes a measure of the dynamic stiffness over a frequency range of 10 to 500 Hz. The fastener employs elastomer in shear and provides a reasonably high lateral stiffness to maintain rail position. The high lateral stiffness and captive design of the top plate also help to reduce rail rotation under lateral load in spite of its low vertical stiffness. This is, perhaps, one of its most important design features. For additional information on direct fixation fasteners, refer to Section 5.4.3 in this handbook.

One feature of a low stiffness fastener is that the rail static deflection will be distributed over more fasteners; thus the rail will appear to be more uniformly supported. Low rail support stiffness is advantageous in reducing the pinned-pinned mode resonance frequency due to discrete rail supports, as well as the vertical resonance frequency for the rail on the fastener stiffness.

The ratio of vertical dynamic-to-static stiffness describes the quality of the elastomer; a low ratio is very important for vibration isolation. The ratio is obtained by dividing the dynamic stiffness (measured with a servo-actuated hydraulic ram) by the static stiffness determined over the majority of the load range. A desirable upper limit is 1.4, easily obtained with fasteners manufactured with a natural rubber elastomer or derivative thereof. Dynamic-to-static stiffness ratios of 1.3 are not uncommon with natural rubber elastomer in shear. As a rule, elastomers capable of meeting the limit of 1.4 are high quality and generally exhibit low creep. Neoprene elastomers provide a dynamic-to-static stiffness ratio greater than 1.4 and can be as high as 4. (Note: A neoprene elastomer may be desirable for controlling rail noise radiated from at-grade or aerial structure track due to the material damping of the elastomer, which absorbs rail vibration energy. Thus, the choice of elastomer may depend on whether groundborne vibration isolation or airborne noise reduction is desired.)

High lateral restraint is often incompatible with vibration isolation design requirements. Therefore, a stiffness range is desirable for the lateral restraint to ensure both an adequate degree of horizontal position control and sufficient lateral compliance to provide vibration isolation. Hard snubbers are undesirable in fasteners, because they limit vibration isolation to the vertical direction only. The design principle is to provide a three-degree-of-freedom isolation.

9.2.5.3.5 Rail Grinding

Rail grinding to eliminate checks, spalls, and undulation of the rail head reduces groundborne noise and vibration, provided that the vehicle wheels are new or recently trued. This applies especially to corrugated rail track. Rail grinding to reduce ground vibration at low frequencies must remove long wavelength roughness and corrugation, which may require special grinders with long grinding bars or special controls.

9.2.5.3.6 Rail Straightness

Though often overlooked or not considered during track design, rail straightness is fundamentally important in controlling low frequency ground vibration in critically sensitive areas. Roller straightened rails have produced ground vibration frequency components that can be related to the straightener's roller diameter. More recently, substantial vibration was generated at residential structures located adjacent to a main line freight railroad alignment after replacing "gag-press" straightened rail with roller straightened rail with excessive vertical undulation. Narrowband analyses of the wayside ground vibration data identified a linear relation between frequency peaks and train speed that related directly with the roller diameter of the straightening machine. Subsequent field measurements of rail profile with a laser interferometer corroborated the vibration data. The roller straightened rail was replaced with new rail that was also roller straightened, but to British standards. Repeat measurements indicated a substantial reduction of ground vibration, even though the effects of the roller straightener pitch diameter were still identifiable in the wayside ground vibration spectra.[18,19]

This experience leads to the recommendation of "super-straight" rail for sensitive areas where a low-frequency vibration impact is predicted and unwanted. Examples include alignments in very close proximity to sensitive receivers of all types in areas with very soft soil. Controlling low-frequency vibration due to rail undulation by controlling rail straightness is far less costly than the installation of a floating slab track structure. Soft fasteners would provide no positive benefit, and may even exacerbate low-frequency vibration. Corrective rail grinding is incapable of removing rail height undulation over long wavelengths of 2 meters (6 feet) or more. U.S. steel suppliers have not produced rail with an adequate straightness specification. However, such rail is available from European manufacturers, where high-speed rail systems require strict adherence to straightness limits.

9.2.5.3.7 Vehicle Primary Suspension Design

Vehicle primary suspension design is not part of track design, but has a direct bearing on wayside ground vibration amplitudes. Selection of trackwork vibration isolation provisions should ideally be based on the type of vehicle involved. In general, vehicles with soft primary suspensions produce lower levels of vibration than vehicles with stiff suspensions. Differences in suspension characteristics may be sufficient to eliminate the need for floating slab isolation at otherwise critically sensitive locations. Introduction of vehicles with stiff primary suspensions relative to existing vehicles with soft suspensions may introduce vibrations in the 10- to 25-Hz frequency region. Unfortunately, the track design is often blamed.

The selection of chevron-type suspension systems in lieu of stiff rubber journal bushing suspension systems may provide sufficient vibration reduction to reduce the need for other vibration isolation provisions in the frequency range of about 16 to 31.5 Hz. Most modern light rail transit vehicles in the U.S. incorporate chevron primary suspension systems with low vertical stiffness, thus reducing the demand on vibration isolation elements in the track. However, a chevron suspension design is no guarantee of low stiffness. If the vehicles have stiff primary suspension systems, particular attention should be paid to low-frequency vibration control in track at the primary suspension resonance frequency.

9.2.5.3.8 Resilient Wheels and Rail Head Ball Radius

Resilient wheels may provide some degree of vibration isolation above 20 to 50 Hz, depending on elastomer stiffness. However, light rail systems have experienced substantial ground vibration from urethane embedded track due to corrugation with vehicles using resilient wheels mounted on mono-motor trucks. Numerical modeling suggested that a vertical resonance exists in the wheel and track system at a frequency coincident with the corrugation frequency. Other factors are likely relevant. More research is required to further define the cause of this type of corrugation and determine which, if any, track design parameters may influence its generation.

9.2.5.3.9 Subgrade Treatment

The vibration amplitude response of soil is, roughly, inversely proportional to the stiffness of the soil. Therefore, stiff soils tend to vibrate less than soft soils. Grouting of soils or soil stabilization with lime or cement is attractive where very soft soils are encountered, such as soft clays or sands. Unfortunately, large volumes of soil would have to be treated; this would probably not be attractive for vibration control unless such treatment were necessary for structural support. Test data have not been developed for predicting the performance of soil cement or lime stabilization of track subgrades. Grouting is expected to have a significant though possibly mixed effect on ground vibration. Grouting should increase the efficiency of vibration propagation at high frequencies between track and building structures, but reduce the vibration energy input into the soil at low frequencies. Tests at one site indicated low levels of vibration for alluvial soils that had been pressure grouted to prevent building settlement. Additional testing and evaluation are necessary.

9.2.5.3.10 Special Trackwork

Turnouts and crossovers are sources of vibration. As the wheels traverse the frogs and joints, impact forces are produced that cause vibration. Grinding the frog to maintain contact with a properly profiled wheel can minimize impact forces at frogs. Spring frogs and movable point frogs are designed to maintain a continuous running surface. Spring frogs are practical for low speed turnouts, while movable point frogs are more suited to high-speed turnouts. Refer to Chapter 6 for additional discussion on frog types.

9.2.5.3.11 Distance

The track should be located as far from sensitive structures as possible within a right-of-way. Where wide rights-of-way exist, there may be some latitude in locating the track. A shift of as little as 3 meters (10 feet) away from a sensitive structure may produce a beneficial reduction of vibration. Avoid locating track close to sensitive structures where sufficient right-of-way width exists to alter the alignment.

9.2.5.3.12 Trenching and Barriers

Open trenches have been considered for vibration reduction, but are of limited effectiveness below 30 Hz for a depth of 7 meters (20 feet) and even less for shallower trenches. At higher frequencies, the vibration reduction of a trench filled with styrofoam may be as little as 3 to 6 dB. Concrete barriers embedded in the soil have also been considered. While they may interrupt surface wave propagation, their mass must be substantial to provide sufficient vibration reduction. Detailed finite element modeling is necessary in this case to predict performance.

9.2.5.3.13 *Pile-Supported Track*

Piling used to reinforce a track support system can be effective in reducing ground vibration over a broad range of frequencies. An example would be a concrete slab track supported by piles or ballasted track on a concrete trough supported by piles. Performance improvement is likely to be substantial if the piles can be extended to rock layers within about 20 meters (65 feet). Standing wave resonances may occur in long piles, so that there is a limit on the effectiveness of piles in controlling audible groundborne noise. Unfortunately, piles may interfere with utilities and the cost of piling is substantial. Piling may be attractive for civil reasons, however, and the added benefits of vibration control can be realized with appropriate attention directed to design.

9.3 REFERENCES

[1] *Journal of Sound and Vibration*, Academic Press, Ltd., Published by Harcourt Brace Jovanovich, London

[2] Nelson, J. T., *Wheel/Rail Noise Control Manual, TCRP Report 23,* Wilson, Ihrig & Associates, Inc., for TRB National Research Council.

[3] Nelson, J. T., H. J. Saurenman, G. P. Wilson, *State-of-the-Art Review: Prediction and Control of Ground-Borne Noise and Vibration from Rail Transit Trains*, Final Report, Wilson, Ihrig & Associates, Inc., for US Department of Transportation, Urban Mass Transit Administration, UMTA-MA-06-0049-83-4.

[4] Saurenman, H. J., G. P. Wilson, J. T. Nelson, *Handbook of Urban Rail Noise and Vibration Control*, Wilson, Ihrig & Associates, Inc., for USDOT/TSC, 1982, UMTA-MA-06-0099-82-1.

[5] *Transit Noise and Vibration Impact Assessment*, for the U.S. Department of Transportation, Federal Transit Administration, April 1995.

[6] ISO 2631, Mechanical Vibration and Shock-Evaluation of Human Exposure to Whole-Body Vibration, 2nd Ed., International Organization for Standardization (ISO), 1997

[7] *ANSI S3.29-1983, Guide to the Evaluation of Human Exposure to Vibration in Buildings*, American National Standards Institute, 1983 (See subsequent revisions)

[8] *ANSI S3.29-1983, Guide to the Evaluation of Human Exposure to Vibration in Buildings,* American National Standards Institute, 4 April 1983. (This standard has been recently revised.)

[9] Remington, P. J., *The Estimation and Control of Rolling Noise Due to Roughness*, BBN Report No. 8801, for ERRI Committee C 163, 1994.

[10] Kalousek, J., and K. L. Johnson, *An Investigation of Short Pitch Wheel and Rail Corrugation on the Vancouver Skytrain Mass Transit System,* Proc. Institute Mechanical Engineers, Part F, Vol. 206 (F2), 1992, pp. 127-135.

[11] Remington, P. J., *Wheel/Rail Rolling Noise, What Do We Know, What Don't We Know, Where do We Go from Here*, Journal of Sound and Vibration, Vol 120, No. 2, pp203-226.

[12] Ver, I. L., C. S Ventres, and M M. Miles, *Wheel/Rail Noise – Part III: Impact Noise Generation by Wheel and Rail Discontinuities,* Journal of Sound and Vibration, Vol 46, No. 3, 1976, pp 395-417.

[13] Rudd, M J., *Wheel/Rail Noise, -Part II: Wheel Squeal,* Journal of Sound and Vibration, 46(3),1976. pg385

[14] *Transit Noise and Vibration Impact Assessment*, Harris, Miller, Miller & Hanson, Inc., for the Federal Transit Administration, U.S. Department of Transportation, Washington, DC. April 1995 DOT-T-95-16.

[15] Crockett, A. R., and R. A. Carman, *Finite Element Analysis of Vibration Levels in Layered Soils Adjacent to Proposed Transit Tunnel Alignments,* Proceedings of Internoise 97, Budapest, Hungary, 25-27 August 1997. Institute of Noise Control Engineering.

[16] Nelson, J. T., *Prediction of Ground Vibration Using Seismic Reflectivity Methods for a Porous Soil,* Proceedings of the IWRN 1998 Conference, Isle de Embiez, November 1998.

[17] Nelson, J. T., *Recent Developments in Ground-Borne Noise and Vibration Control,* Journal of Sound and Vibration, 193(1), pp.367-376, (1996)

[18] Nelson, J. T., and S. L. Wolfe, *Kamloops Railroad Ground Vibration Data Analysis and Recommendations for Control,* Technical Report, Wilson, Ihrig & Associates, Inc., for CN Rail.

[19] Nelson, J. T., *Recent Developments in Ground-Borne Noise and Vibration Control,* Journal of Sound and Vibration, 193(1), 1996, p.373.

Chapter 10—Transit Signal Work

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CHAPTER 10—TRANSIT SIGNAL WORK

10.1 TRANSIT SIGNAL

10.1.1 General

Street-running light rail systems can be operated without signals only at low speeds. Train operators must obey the local traffic laws and yield the right-of-way (ROW) to traffic on the tracks. In higher speed operations on exclusive rights-of-way, trains use signal systems to avoid collisions with other trains and with street vehicles crossing the tracks.

The principles of light rail transit signaling are similar to railroad main line signaling in providing for the safe movement of trains. The track is divided into segments called blocks. Signals keep two trains from occupying the same block at the same time and generally keep an empty block between trains that are travelling at the posted speed. Track circuits detect trains in a block. Block systems ensure train separation with safe stopping distance. Interlocked switches and crossovers protect against conflicting routes and improper switch operation. Transit signaling also provides block supervision as required for street operation, warning of approaching trains at grade crossings and supervising coordination with proximate vehicle traffic schemes as required for system performance and safety.

Typically, there are six light rail transit signaling designs:

- No signaling at all: the system operates with fixed-guideway vehicles in a free-wheeled community with no resultant speed advantage over bus operation
- No signaling except to provide preferential access over cross traffic: the LRV uses signal preemption devices such as overhead wire contractors, wheel detectors, induction couplers, or other non-vital devices to improve speed by eliminating intersection delays
- Power operation of track switch facing points: power on/off switches, time sequences, induction couplers, or other non-vital devices are used to improve LRV speed by eliminating stops to throw switches, thereby allowing trains to keep moving
- Block supervision (single track, low-speed operation): similar to preemptive devices, allows an opposing train to advance without incurring schedule delay if possible
- Block and switch protection: basic railroad signaling technology employing wayside signals, sometimes in conjunction with mechanical or inductive train stops, to provide safe operation (newer light transit systems have employed cab signals with or without train stops for continuous speed control)
- Grade crossing warning: based on railroad signaling technology, gates and flashers eliminate slow downs to determine if grade crossings are clear; generally recognized as the most effective type of crossing warning system, allowing improved LRV operating speed

The choice of which system is most appropriate for a specific section of track is based on operational and political considerations. A light rail system may utilize different signal technologies at different locations based on these concerns. A street-running operation with slow speed requires different controls than a high-speed operation on an exclusive ROW.

The appropriate level of signal automation varies by transit systems. The optimum cost/benefit ratio depends on local circumstances and is determined by the authority responsible for providing the service. These various types of signaling have little impact on the track designer, but the interfaces are important. Design differences in light rail systems are primarily related to their operating environments.

10.1.2 Transit Signal System Design

The system designer is obliged to consider the signaling technology available to provide the desired system operating performance at the least total cost. Within the scope of light rail transit applications, a well-established catalogue of proven technology is available.

Transit signal system design must consider not only what technology is available, but also the most rational combination of equipment for a particular application. Signal systems are customized or specified by each transit system to provide safe operation at an enhanced speed. The location of signal block boundaries is based on headway requirements and other considerations such as locations of station stops, highway crossings, and special interlocking operating requirements.

Selection and spacing of track circuits for ac and dc propulsion systems are influenced by many factors. These include: the degree of defective insulated rail joint detection or broken rail protection required, the likelihood of stray current, the frequency of interfering sources of power (propulsion and cab signaling), and the inherent advantages of various types of track circuits.

10.2 SIGNAL EQUIPMENT

10.2.1 Switch Machines

10.2.1.1 General

Track switches can be operated by hand or by power. When time and convenience are important, automated switch machines are advantageous. Switch machines may be controlled from a central control facility or by the vehicle operator.

Switch machines are used on main lines, interlockings, and yards. Switch machines can operate a switch, derail, or wheel stop. The type of switch machine selected is dependent on operating parameters, clearances, and the type of track installation—timber or concrete switch ties or direct fixation track.

10.2.1.2 Trackwork Requirements

Switch machines in ballasted track rest on headblock switch ties and interface with turnouts through operating and switch rods. This interface is often complicated, particularly in direct fixation (DF) or embedded track, where blockouts in the concrete must be provided for proper clearance. The following elements associated with track and structure design should be considered when designing turnout switch machines:

- Size of turnout or crossover
- Number of head ties
- Size, height, width, and length of head tie
- Type of number one rod—vertical or horizontal
- Thickness of number one rod
- Type of basket on number one rod
- Distance from centerline of switch machine to gauge line of the nearest rail
- Types of tie plate for number one and two ties

- Tie or mounting spacing between switch machine rods
- Type of derail or wheel stop
- Location of mounting of switch machine to ties or surface
- Insulation of trackwork switch, basket, and tie plate
- Distance to throw of the switch machine
- Location of extension plate mounting holes and interface plate
- Lubrication of switch plate and track layout

10.2.1.3 Types of Switch Machines

10.2.1.3.1 Electric

Electric switch machines are common for light rail operations because of the ready availability of electric power throughout the system. Electric switch machines are rugged, reliable units designed for any installation where electric power is available. Electric switch machines may be used in main line, interlocking, and yard service. For installations in which extra vertical clearance is needed for a third-rail shoe, a low-profile electric switch machine can be used. Electric switch machines are available in a variety of operating speeds and motor voltages.

Switch machines are usually specified to meet the requirements of AAR Load Curve 14511, providing ample thrust to operate the heaviest of switches. Electric switch machines are normally provided with one throw rod, one lock rod and one point detector rod connected to the rails. They are also available with two lock rods and two detector rods. The track designer and signal designer must coordinate to ensure the specifications provide these critical elements. Gauge plate extensions can be supplied that attach the switch machine to the track switch to aid in holding the adjustments of the switch machine. Electric switch machines are usually installed adjacent to the normally closed point of the switch.

10.2.1.3.2 Electro-pneumatic

Electro-pneumatic switch machines require a reliable source of compressed air. While this is economical for heavy rail transit, which features short block lengths and frequent interlockings, the economics on light rail lines usually make air power switches too costly.

10.2.1.3.3 Hand-Operated

Hand-operated switch machines are typically used where facing-point lock protection is required to help safeguard the movement of high-speed main line traffic over a switch. These switch machines contain a locking bar that, with the switch in the normal position, enters a notch in the lock rod. This arrangement locks the switch points in their normal position to provide facing-point lock protection.

10.2.1.3.4 Yard

Yard electric switch machines are simple and compact machines designed for transit yard application. For installation in tight spaces, the low-profile yard electric switch is available with external switch indicator lights. Unlike many main line switch machines, some yard electric switch machines can handle trailing moves at maximum yard speeds up to 32.2 kilometers per hour (20 miles per hour). The yard switch machine can be used in either horizontal or vertical No. 1 rod switch layouts. If point detection is required, an additional circuit controller can be installed. Built to fit practically any yard switch, this machine can be adjusted for throw, from 114 millimeters (4.5 inches) up to a full 140 millimeters (5.5 inches).

Electro-pneumatic switch machines are also available for yard application, and a compressed air plant at the yard or maintenance facility may make them economical.

10.2.1.3.5 Embedded (Surface)

Embedded (surface) switch machines are designed to throw all tongue and mate, double-tongue, or flexible switches with a maximum switch throw of 114 millimeters (4.5 inches). The embedded switch machine is installed between the rails (preferred) or on the outside of the switch tongue on a paved street. Embedded switch machines can be powered from available 600 to 750 Vdc or from an ac source through a transformer and bridge rectifier unit. The switch tongue can be trailed without damage to the embedded switch machine and can be thrown manually in an emergency.

Drainage of switches and switch machines is critical. The embedded switch machine track box should be drained to a nearby storm pipe, because an undrained box collects a mixture of sand, water, salt, etc., that increases wear on moving parts and prevents their proper lubrication. Normally a copper bond wire is installed between the box and rail to complete the circuit. This can be omitted if the power source is a rectifier. Where circuit controllers are used, either one or two conduits are required to accommodate the cables. A cleanout box is installed to provide access to connecting rod adjusting nuts if they extend beyond the switch.

10.2.2 Impedance Bonds

10.2.2.1 General

Impedance bonds are necessary when insulated track joints are used to electrically isolate track circuits from each other. The impedance bonds permit propulsion current to flow around the insulated joints while inhibiting the flow of signal current between adjacent track circuits. Audio frequency track circuits are separated from each other by using a different frequency in each circuit; as such they do not normally require insulated joints to isolate the track circuits. Insulated joints are used with audio frequency track circuits when a true definition is needed, such as at signal locations. The stagger between insulated joints should be 610 millimeters (2 feet) or less for transit signaling to reduce the amount of cable needed as well as the unbalance in the current in the rails associated with impedance bonds.

10.2.2.2 Trackwork Requirements

The following elements associated with track and structure design should be considered when designing impedance bonds:

- Tie spacing for signal equipment
- Location of tie or direct fixation mounting holes for signal equipment
- Location of impedance bond, either between or outside the rails
- Location of guard and restraining rails
- Location and spacing of insulated joints
- Space for cables and conduit to pass beneath the rail
- Conduit and cable location for signal equipment

10.2.2.3 Types of Impedance Bonds

10.2.3.3.1 Audio Frequency

Audio frequency impedance bonds are designed to terminate each end of audio frequency track circuits in transit installations.

The impedance bonds provide:

- Low resistance for equalizing propulsion current in the rails
- Means of cross bonding between tracks
- Connection for negative return

- Means of coupling the track circuit transmitter and receiver to the rails
- Means of coupling cab signal energy to the rails
- Means of inhibiting the transmission of other frequencies along the rail

10.2.3.3.2 Power Frequency

Power frequency bonds are designed for use in ac or dc propulsion systems that use insulated joints to isolate track circuit signaling current from signaling currents of adjacent circuits, but permit propulsion current to flow around the joints to or from adjacent track circuits. AC impedance bonds are usually rated for 300 amps per rail and dc impedance bonds are usually rated for between 1,000 and 2,500 amps per rail. Typically, power frequency impedance bonds are installed in pairs at insulated joint locations and mounted between the rails across two adjacent ties.

10.2.3 Loops and Transponders

10.2.3.1 General

Loops and transponders are used to transmit information to the train independent of track circuits. They may be found in all types of trackwork and can be used for intermittent transmission or continuous control systems. In determining the type or location of loops or transponders to be used for a light rail transit system, consideration should be given to the operation plan, type of track circuits, propulsion system, and train control system that is installed.

10.2.3.2 Trackwork Requirements

The following elements associated with track and structure design should be considered when designing loops or transponders:

- Location of loop or transponder inside or outside the rail
- Attaching the loop or transponder to the rail
- Tie spacing and mounting method for loop or transponder
- Cable and conduit location for signal equipment
- Block out area for loop or transponder and junction box

10.2.3.3 Types of Loops and Transponders

10.2.3.3.1 Speed Command

Speed command loops are used to provide a means for coupling cab signal energy to the rails. Typically, speed command inductive loops are installed with or without rubber hoses within the turnout diverging track. They may be attached to the tie or concrete, or clipped to the rail. The rubber hose with wire inside is installed near the inside of the rail at interlockings and turnout switches. These loops provide isolation from the track circuits.

10.2.3.3.2 Train Location

Train location loops are designed to provide more precise definition of a train's location and two-way train/wayside communication. A wire loop installed between the rails and on ties links the train to the rails. The horizontal loop of the wire is directly mounted or placed in a heavy polyvinyl chloride (PVC), epoxy, or fiberglass (FRE) conduit that may also be encased in pavement.

10.2.3.3.3 Traffic Interface

Loops or transponders can be used to pre-empt traffic signals or provide phasing command and release of traffic control devices.

10.2.3.3.4 Continuous Train Control Loop

Typically loops between stations are transposed at regular intervals. This provides a signal to the on-board equipment that can be used to recalibrate an on-board odometer. In station areas, short loops may be provided for accurate station stopping purposes.

10.2.3.3.5 Transponders

Transponders are designed to transfer data to the vehicle or wayside equipment. Transponders or antennae may be mounted overhead, on the wayside, or embedded between the rails.

10.2.4 Wheel Detectors/Axle Counters

10.2.4.1 General

Wheel detectors and axle counters are used to detect trains without relying on a track circuit. Since they do not require insulated joints, they cause less interference with traction return current than detection devices that depend on electrical signals in the rails. When used without track circuits or cab signaling within the rails, they eliminate the need for insulating switch rods. However, they are unable to detect broken rails. In selecting the type and model of wheel detector/axle counter, consideration should be given to the operation and mounting method used.

10.2.4.2 Trackwork Requirements

The following elements associated with track and structure design should be considered when designing wheel detectors/axle counters:

- Type and size of rail
- Mounting hole size
- Conduit and cable location
- Rail grinding
- Maintenance
- Block out requirements or box requirement

10.2.4.3 Types of Wheel Detectors/Axle Counters

The wheel detector/axle counter unit consists of a detector head or mechanical detector arm, mounting hardware, logic board, and interconnecting cabling. Wheel detectors and axle counters are mounted with clamps that attach to the base of the rail or are bolted directly to the web. The wheel detectors/axle counters are activated when a vehicle passes. The magnetic wheel detector/axle counter is independent of the wheel load and subjected to almost no wear, since there is no mechanical interaction between the detector and vehicle wheels.

10.2.5 Train Stops

10.2.5.1 General

Train stops trip the train's braking mechanism if a restrictive cab signal aspect or signal is ignored. They can be inductive units or electrically-driven mechanical units. In designing train stops, consideration should be given to the location of vehicle equipment, type of trackbed, operation (directional or bi-directional), relationship to wayside signal layouts, and location of the train stop elements. Train stops are used in exclusive ROWs and are not conducive to street-running applications.

10.2.5.2 Trackwork Requirements

The following elements associated with track and structure design should be considered when designing train stops:

- Type of track—ballasted, direct fixation, or dual block
- Tie spacing
- Type of tie—timber or concrete
- Location of train stop
- Conduit and cable location
- Relationship to signals, insulated joints, and impedance bonds

10.2.5.3 Types Of Train Stops

10.2.5.3.1 Inductive

Inductive train stops are designed with a magnetic system that interacts with carborne vehicle control equipment. Both the vehicle magnet and the track magnet need to be strategically mounted on the vehicle and track, respectively.

10.2.5.3.2 Electric

The key component of the electric train stop is the driving arm, which is pulled to the clear position 12 millimeters (0.5 inches) below the top of the running rail by the electric motor and returned to its tripping position by a spring. Electric train stops are usually mounted on plates midway between two rails.

10.2.6 Switch Circuit Controller/Electric Lock

10.2.6.1 General

A switch circuit controller is a mechanism that provides an open or closed circuit indication for a two-position track appliance, such as a switch point. A mechanical linkage to the crank arm of the controller actuates its normal/reverse contacts. The switch circuit controller provides break-before-make contacts that allow separate adjustments at each end of the stroke. Commonly used to detect switch positions, the switch circuit controller can be used to detect positions of derails, bridge locks, slide detectors, and tunnel doors. They can shunt track circuits as well as control relay circuits. Electric switch locks prevent unauthorized operation of switch stands, hand-throw switch machines, derails, and other devices. In determining the rods and type of switch circuit controller/electric locks, consideration should be given to operation, type of switch or derail, mounting, and clearances. The switch circuit also protects vehicles by ensuring that the switch points are closed.

10.2.6.2 Trackwork Requirements

The following elements associated with track and structure design should be considered when designing wheel switch circuit controller/electric locks:

- Type of track bed—ballasted, direct fixation, or dual block
- Type of tie—timber or concrete
- Length of tie
- Left or right hand layout
- Type of hand-operated switch machine or derail
- Number and location of connection lugs on derail
- Location of conduit and cable

10.2.6.3 Types of Switch Circuit Controller/Electric Lock

10.2.6.3.1 Switch Circuit Controller

A switch circuit controller is a ruggedly constructed unit commonly used with switches to detect the position of switch point rails. The switch circuit controller has a low clearance profile and is mounted on a single tie.

10.2.6.3.2 Electric Lock

An electric switch lock operates by a means of a plunger that is lowered into a hole in the lock rod connected to switch points, derails, or other devices. Some electric switch locks are designed for low-profile application to locking levers located between the rails at the middle of hand-operated crossovers, where clearance is limited to 280 millimeters (11 inches). Another electric switch lock secures the hand-throw lever on a switch stand or switch machine in the normal position.

10.2.7 Signals

10.2.7.1 General

Wayside track signals are usually light fixtures mounted on poles or at ground level (dwarf signals) next to switches. One installation even uses airport runway lights mounted between the rails. Several variations of color-light signals with various indications are currently in use on light rail systems. In determining the type and configuration of wayside signals to be used, consideration should be given to operation, clearances, signal layout, track layout, right-of-way, and insulated joint locations.

10.2.7.2 Trackwork Requirements

The following elements associated with track and structure design should be considered when designing signal mast installations:

- Insulated joint locations
- Right-of-way clearances
- Conduit and cable location
- Vehicle clearances
- Stopping distances

10.2.7.3 Types of Signals

Long-range color-light signals consist of one or more light units with a 213-millimeter (8.4-inch) outer lens for high signals and a 162-millimeter (6.4-inch) lens for dwarf (low) signals. These high and dwarf signals have lenses for both tangent and curved tracks. The dwarf signals are designed for direct mounting on a ground-level pad such as a concrete foundation. The main line high signals have backgrounds, hoods, pipe posts, ladders, pole mounting brackets, and foundations.

Transit color-light signals are compact units designed for lines where clearances are very limited. A 127-millimeter (5-inch) lens signal is typically used in subway installations where space is limited, while a 162-millimeter (6.4-inch) signal is used for outdoor service. Transit signals are supplied with brackets for mounting on subway walls, ceilings, or poles.

Signals are normally installed on the train operator's side of the tracks with adequate horizontal/vehicle clearance from gauge of rail. Where insulated joints are used, the signal is typically located between the two insulated joints in double-rail territory. The signal can be moved ahead of the insulated joints to a distance no greater than the overhang of the vehicle.

10.2.8 Bootleg Risers/Junction Boxes

10.2.8.1 General

Bootleg risers/junction boxes provide a central termination point for signal cables. Bootleg risers/junction boxes come in a variety of sizes, with or without pedestals, and are constructed of cast iron or steel. Based on the application of the bootleg risers/junction boxes, the location can be in the center of tracks, outside or inside the gauge side of the running rail, outside the end of tie, outside the toe of ballast, or next to the switch machine or other signal appliance. In selecting the type and size of bootleg risers/junction boxes, consideration should be given to the type of trackbed, cable, signal equipment, and mounting method used.

10.2.8.2 Trackwork Requirements

When designing bootleg risers/junction boxes, the following elements associated with track and structure design should be considered:

- Conduit and cable location
- Type of trackbed—ballast, direct fixation, or dual block
- Tie spacing
- Maintenance

10.2.8.3 Types of Bootleg Risers/Junction Boxes

10.2.8.3.1 Junction Boxes

Pedestal-mounted junction boxes are typically used in ballasted track at switch machines, switch circuit controllers, track circuit locations, etc. as a central termination point for underground cables. A variety of adapter plates allow the junction box to be used with air hose adapters and connectors.

10.2.8.3.2 Bootleg Risers

Bootleg risers are designed as a termination point between the underground cable and the track wire to the rail or signal device. They are available with a bottom outlet, as well as side and bottom cable outlets. A typical bootleg riser installation would locate the riser box in the center of the track with the top slightly below the top of ties.

10.2.9 Switch and Train Stop Heaters/Snow Melters

10.2.9.1 General

Switch and train stop heating systems are designed to keep rail switches, switch rods and tongues, and train stop arms free of ice and snow in a predictable and reliable fashion. In designing the heating system, consideration should be given to the type of power available, type of trackwork, type of track bed, operation, type of train stop, type of switch machine, and mounting method used.

10.2.9.2 Trackwork Requirements

When designing switch heaters and snow melters, the following elements associated with track and structure design should be considered:

- Size of turnout or crossover
- Type of switch point —curved or straight
- Maintenance
- Type of rail brace with notch, if required
- Conduit and cable location
- Junction box(es) location(s)
- Length of switch point
- Number of switch rods
- Type of trackbed—ballasted, direct fixation, or dual block

10.2.9.3 Types of Switch/Train Stop Snow Melters

There are several snow melter systems commonly used in the transit industry. The most popular system features tubular resistor electric snow melters that can be installed on either the field side or gauge side and either at the underside of the rail head or at the base of the rail. For gauge side installation, holes are drilled in the neutral axis of the rail using a clearance drill for heater support clips with 10-millimeter (0.4-inch) bolts. For field side installation, snap-on clamps are used (no drilling is necessary). Tubular electric snow melters mounted on the field side and base of the rail require the special trackwork rail brace to be notched for passage of the snow melter.

The rail web heater can also be used to prevent switches from freezing. The rail web heater is a low-density panel that spans the rail web. It consumes 20 to 40 percent less power than a tubular heater installation Rail web heaters are interconnected to provide more heat to the point and snapped into place using rugged clips and a special clip tool. No braces need to be loosened or grooved to allow installation, which provides for easy removal in the spring prior to track maintenance or repair.

Power is supplied to electric snow melters from the overhead catenary through a snow melter control cabinet or case.

Switch rod heaters are used to melt snow and ice away from switch rods. These switch rod heaters are installed in the bottom of the crib where the switch rods are located. They consist of a steel channel or panel with tubular electric heaters or a series of heating elements attached. The tubular electric heater can be mounted on a swing bracket that clamps to the base of the rail on the field side and is adjustable for all sizes of rails.

Train stop mechanisms can be furnished with hairpin-shaped heaters or heating panels.

Other types of snow melting systems include: oil, natural gas, or an electric high-pressure heating unit that forces hot air throughout the switch area via ducts and nozzles. An alternate snow blower arrangement uses ambient non-heated air to blow snow clear of the switch point areas.

10.2.10 Highway Crossing Warning Systems

10.2.10.1 General

Highway crossing warning systems provide indications to motorists that a light rail vehicle is approaching the crossing. In determining the type and configuration of the highway crossing warning system consideration should be given to LRV operations, type of track circuit, roadway layout and posted speeds, traffic signal(s) location, right-of-way, and clearances. The challenge of fail-safe crossing protection is to protect the LRV and highway traffic without closing the crossing gates for extended periods of time. The federal Manual of Uniform Traffic Control Devices is being updated to include recommendations for light rail vehicle operations.

Crossing gate installations should be interconnected with the traffic signals within 60 meters (200 feet) of the highway grade crossing.

10.2.10.2 Trackwork Requirements

When designing highway crossing warning systems, the following elements associated with track and structure design should be considered:

- Location of insulated joints (if required)
- Location of crossing slabs
- Minimum ballast resistance
- Tie spacing
- Right-of-way clearance to highway crossing equipment
- Conduit and cable location
- Insulation of running rails from each other if a track circuit is used for the warning system

10.2.10.3 Types of Highway Crossing Warning System

A typical highway crossing may consist of flashing light units, gate mechanisms with arms up to 12 meters (40 feet) long, poles, foundations, cantilever assemblies, cables, case or signal houses, junction boxes, and track circuits with island circuits.

10.2.11 Signal and Power Bonding

10.2.11.1 General

Signal and power bonding is used to establish electrical continuity and conductive capacity for traction power return and signal track circuits. It prevents the accumulation of static charges that could produce electromagnetic interference or constitute a shock hazard to track maintenance personnel. It also provides a homogeneous and stable ground plane, as well as a fault current return path.

Power bonding is typically installed at all non-insulated rail joints, frogs, restraining rails, guard rails, and special trackwork locations. Power bonding of the restraining rails requires special attention to avoiding run around paths that can falsely energize the track circuit.

There are basically two types of rail connections used in the transit industry: mechanical and exothermic welding. In determining the type and the amount of signal and power bonding, consideration should be given to type of track circuits, capacity of the traction power equipment, type of rail, vehicle wheels, and the amount of broken rail detected.

10.2.11.2 Trackwork Requirements

The following interface elements associated with track and structure design should be considered when designing signal and power bonding:

- Type and size of rail
- Spaces for bonding to be installed
- Space for signal and power bond passing beneath the rail
- Type of track bed—ballasted, direct fixation, or dual block
- Location of rail joints, insulated or non-insulated
- Location of guard and restraining rail
- Signal cable connection to rail in special trackwork

10.2.11.3 Types of Signal and Power Bonding

Impedance bond leads are factory made to system specifications and impedance bond type for ease of installation, eliminating a typically cumbersome field application. One method of connecting cables to rails is via plug bonds. This method involves drilling a hole in the rail and hammering the plug into the hole. Exothermic welding, on the other hand, generates molten copper to create a solid bond between the cable and rail or between cables. Advantages of exothermic welding vs. plug bonds for connecting signal and power bonding include:

- The installation resistance of a length of exothermic weld bond is less than other types of bonds of the same length and cable stranding. Resistance will not change throughout the life of the bond.
- There is no corrosion between an exothermic weld bond and the rail. Intermittent signal failures due to the varying resistance of a corroded rail joint will be eliminated.
- Bond losses caused by dragging equipment, reballasting, and snowplows are reduced.
- Vehicular traffic will not loosen a properly installed exothermic weld bond.
- Rail head signal bonds that are applied within 125 millimeters (5 inches) of the end of rail (per AAR Part 8.1.20. E.2.c) provide better detection of broken rail than plug bonds that are applied outside of the splice bars.
- Rail web bonds from 14 to 250 square millimeters (0.2 to 0.4 square inches) provide a convenient means of connecting all cable outside the confines of the splice bar, including special trackwork. Located at the neutral axis, the connection is less susceptible to vibration fatigue and is kept clear of dragging equipment and maintenance machinery.
- The exothermic weld process provides an efficient field method for any electrical connection from signal and power to ground.
- The exothermic weld normally outlives the conductor itself.

Advantages of plug bonds vs. exothermic welding for connecting signal and power bonding include:

- The rail connector clamp can connect cables from 250 to 1000 square millimeters (0.4 to 1.6 square inches) to the running rails.

- Mechanical connectors such as plug bonds provide a rail connection without the risk of overheating the rail steel.
- Rail connection can be easily relocated or temporarily removed without grinding the rail or chopping the connection.
- Splice bar to rail web bonds may be used to detect a break in the splice bar itself.
- Where signal bonds cannot be installed from the field side due to tight areas, such as frogs and switches, a multi-purpose bond can be used by drilling through the rail web.

10.3 EXTERNAL WIRE AND CABLE

10.3.1 General

Various types of cable and methods of installation are required for transit signal systems. Main cables are those cables that run between housings or that contain conductors for more than one system function. Local distribution cables are those cables running between a housing and an individual unit of equipment. In selecting the method of installation of external wire and cable, consideration should be given to cost, maintenance, and type of right-of-way.

10.3.2 Trackwork Requirement

When determining the location of external wire and cable the following should be considered:

- Conduit and cable location
- Maintenance of trackwork
- Drainage
- Locations of pull boxes, handholes, manholes, duct banks, etc.
- Compaction of soil and subballast
- Location of cable trough
- Visual impact

10.3.3 Types of External Wire and Cable Installations

10.3.3.1 Cable Trough

A cable trough system is a surface trench that protects and provides continuous accessibility to the signal cables. When installed within the track gauge between two ties, care must be taken in track tamping. Signal cables can exit and enter the cable trough system either from the bottom or sides.

The typical cable trough installation requires a trench of minimum width to provide free access to both sides of the trough while maintaining 200 millimeters (8 inches) of ballast and sub-ballast below the trough. The maximum particle size should not exceed 19 millimeters (0.75 inches). Fill material should not be placed on frozen ground and should be tamped. The cable trough should be placed so that the uppermost part is 25 millimeters (1 inch) higher than the surrounding ground or ballast surface.

The cable trough should be capable of supporting an H-20 load at any point.

10.3.3.2 Duct Bank

The underground duct system should be completely encased in concrete with a minimum clearance of 50 millimeters (2 inches) between conduits and the outside edge and a minimum cover of 300 millimeters (12 inches) for non-metallic conduits and 150 millimeters (6 inches) for rigid metal conduits. If a non-metallic conduit is not encased in concrete, allow 460 millimeters (18 inches) of separation for signal cables carrying 0 to 600 volts. For cables carrying over 600 volts, non-shielded cables should be installed in rigid metal conduits with a minimum cover of 150 millimeters (6 inches) . For cables carrying over 600 volts in rigid non-metallic conduits, the conduit should be encased in no less than

75 millimeters (3 inches) of concrete, or have 450 millimeters (18 inches) of cover if not encased in concrete. Cables are connected to the duct bank systems using handholes, pull boxes, and manholes for proper pulling points or cable routing. A minimum cover of 760 millimeters (30 inches) is recommended for protection (per AAR Part 10.4.40.D.2) when signal cables pass under tracks, ballast, or a roadway.

One of the common problems in constructing light rail systems is the protection of duct banks while the track is being installed. It is important that the responsibility for the care of duct bank risers be assigned in the contract documents.

10.3.3.3 Conduit

Encased or direct burial conduit should be installed as outlined above or as required by the National Electric Code, Article 300-5 and 1110-4(b).

10.3.3.4 Direct Burial

Signal cable and wire should be buried to a uniform depth where practicable, but not less than 760 millimeters (30 inches) below finished grade. Where signal cable and wire is installed within 3 meters (10 feet) of the centerline of any track, the top of the cable should be a minimum of 760 millimeters (30 inches) below the sub-ballast grade.

Signal cables and wires should be laid loosely in the trench on a sand bed a minimum of 100 millimeters (4 inches) thick and covered with a minimum of 100 millimeters (4 inches) of sand before backfilling. Backfill should be compacted to not less than 95% of the maximum dry density of the respective materials as determined by AASHTO Test Designation T-99 or to the original density of compaction of the area, whichever is greater.

Where direct burial signal wires cross the tracks, it is beneficial to install the wiring prior to the tracks. This improves the integrity of the track structure, but complicates signal installation.

Signal cables can be plowed in at a depth of 760 millimeters (30 inches) and 300 millimeters (12 inches) beyond the toe of sub-ballast. Avoiding the track ballast and sub-ballast is important to maintain the structural integrity of the track.

10.4 SIGNAL INTERFACE

10.4.1 Signal-Trackwork Interface

Signaling and trackwork interface issues include:

- Location of insulation joints
- Location and mounting requirements for impedance bonds, train stops, track transformers, junction boxes, and bootleg risers
- Physical connection of impedance bond track cables and track circuit wiring
- Location and mounting layout of track switch operating mechanisms, switch machine surface and subsurface areas (ballast, direct fixation, and embedded)
- Cable and conduit requirements for interconnection of signal apparatus at track
- Location and installation of train stops, inductive loops, transponders, wheel detectors, and axle counters
- Interface pick-up with the traffic signal system
- Location of block outs for wayside signal equipment
- Electromagnetic interference/ electromagnetic compatibility (EMI/EMC)

- Track alignments with cab speeds
- Grounding
- Yard signaling
- Grade crossing warning systems
- Wayside equipment housings and cases
- Corrosion control
- Tie spacing for signal control equipment, impedance bonds, train stops, and switches
- Tie size and length requirements for switches and derails
- Signal cable connection to rail at special trackwork
- Suitable air gap between vehicle antenna/transponder and rails
- Physical connection of switch machines to special trackwork
- Loop or transponder mounting on track for train-to-wayside communication
- Location of insulated joints
- Spaces for cables and conduit passing beneath the rail
- Location of guard and restraining rail
- Horizontal clearance between track and wayside signals and equipment
- Vertical clearance between track and signal equipment
- Space and drainage for switch machine in direct fixation or embedded track
- Provision for installation of snow melters
- Location of switch indicators for embedded track
- Location of cross bonding and negative return cables
- Location of speed limits
- Ballast resistance

10.4.2 Signal-Station Interface

The following signal equipment is typically installed at station locations: impedance bonds, inductive loops, bootleg risers, junction boxes, and transponders. If the station is located near an interlocking or highway crossing, there should be sufficient room from the end of platform to the signal equipment (impedance bonds and signals) and insulated joints if required.

10.4.3 Signal-Turnout/Interlocking Interface

The following signal equipment is typically located at turnouts and interlockings: switch machines; impedance bonds; inductive loops including speed command loops; train stops; bootleg risers; junction boxes; switch controllers; electric locks; transponders; wire and cables; signal and power bonding; cases/signal equipment houses; signals; and snow melter systems. The design of the track circuit and fouling protection used will determine the location of insulated joints in the special trackwork. Typically in transit applications, the insulated joint should be located approximately 7 to 7.6 meters (23 to 25 feet) ahead of the switch points to allow for the use of track. The size of the turnouts and crossovers determines the speed at which the train can operate. This speed should be one of the available cab speeds. The insulted joint for the turnout must be located with a minimum of clearance taking into account the longest overhang of any equipment that may operate on the track.

10.5 CORROSION CONTROL

Leakage of stray currents into the ballast bed and earth can be a significant problem if the cables running from the rails are electrically connected to the impedance bond housing case and the case is in contact with the earth. This can occur if the cases are mounted on reinforced concrete where the mounting bolts contact the re-bar, if the bottom of the case is resting on concrete, or if dirt and debris accumulate between the bottom of the case and the concrete. An accumulation of ballast, dirt, or other debris around the locations where the cases are installed along the right-of-way can also provide a path for current leakage. This type of installation can result in a continuous maintenance problem if an effectively high rail-to-earth resistance is to be achieved.

Some impedance bonds are located outside the tracks on timber ties to eliminate points of possible contact with earth. The center taps of the impedance bonds should be insulated from the mounting case.

Yard tracks should be isolated from the main line tracks to reduce corrosion. For additional information on corrosion control, refer to Chapter 8.

10.6 SIGNAL TESTS

10.6.1 Switch Machine Wiring and Adjustment Tests

Switch machine wiring and adjustment tests verify the wiring and adjustment of the switch machine. They should preferably be carried out, in conjunction with the track installer, to confirm throw rod capability, ensure point closure, and ensure proper nesting of the switch point rail to stock rail.

10.6.2 Switch Machine Appurtenance Test

Switch machine appurtenance tests verify the integrity of switch machine layout by taking resistance measurements across the following assemblies:

- Center insulation of the front rod
- Front rod to switch point
- No. 1 vertical or horizontal switch rod center insulation
- Throw rod insulated from No. 1 switch rod
- Point detector piece insulated from switch point
- Lock rod insulated from front rod
- Other vertical rods as required per layout
- Switch machine insulated from the running rails

10.6.3 Insulated Joint Test

Insulated joint tests measure the resistance between two ends of the rail separated by insulating material. An insulated joint checker requires the traction power system to be disconnected. Any reading under 30 ohms should be evaluated. Measurements for a set of insulated joints should be within 30 percent of each other or they should be rechecked. Insulated rail joint tests for ac track circuits can be performed using a volt-ohmmeter.

10.6.4 Impedance Bonding Resistance Test

Impedance bonding resistance tests ensure that a proper connection has been made using a low-resistance ohmmeter.

10.6.5 Negative Return Bonding Test

Negative return bonding tests verify the resistance of each mechanical or welded power bond using a low-resistance ohmmeter.

10.7 SUMMARY

Communication-based signaling systems are replacing traditional track circuits. They eliminate the need for impedance bonds, signal bonding, and bootleg risers and greatly reduce the number of signal wires and cables. Transit system designers are challenged to find the correct level of transit signaling for each segment of a light rail transit line. The different needs for signals are indicated by the wide variety of right-of-way types and operating conditions, coupled with the broad catalogue of proven, available transit signal equipment. This should encourage designers to seek the technical solution that will both respond to conditions and minimize total costs.

Track designers need to coordinate closely with signal designers to determine the types of signal equipment that will be installed on the trackway. Once the equipment is identified, the interfaces with the track must be defined so a coordinated system can be constructed. Construction phasing is an important part of this coordination.

Chapter 11—Transit Traction Power

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CHAPTER 11—TRANSIT TRACTION POWER

11.1 GENERAL

Light rail systems, by definition, use electrical power from overhead wires to provide traction power to the light rail vehicles. Light rail systems use the rails, in conjunction with negative cables, as the return conductor to the negative terminal of the rectifiers. Therefore, the electrical properties of the rails and tracks require special consideration.

Theoretically, the traction current flows along the overhead contact system to the train from the substation and back to the substation through the running rails. To obtain good conductivity for the track as a whole, a rail system must have a low resistance not only for reasons of economy but also for safety. This requires a low voltage drop in the rails.

The traction power system consists of the:

- Traction power substation
- Cables connecting this substation to the distribution system
- Wayside distribution system (catenary or contact wire) providing adequate voltage levels throughout the alignment
- Return system cables connecting the running rails to the substation
- Corrosion control drainage system directing stray return current back to the appropriate substation

11.1.1 Interface

There are four elements in the traction power system that affect, or are affected by, trackwork design, construction, and maintenance:

- Traction power positive supply system, including substation locations
- Wayside catenary distribution positive system, providing power to the vehicles
- Traction power negative return through the rails
- Corrosion control measures to mitigate the effects of stray direct currents passing through adjacent conduits, pipes and cables

11.2 SUBSTATION LOCATIONS

The design of the track structure interface with the traction power system must consider the cable and conduit access that will pass under the track at substation locations to provide power to the catenary pole. Cables and conduits for the return current to the substation will also pass under the track.

The location of traction power substations is developed using a computerized train performance program that simulates proposed peak operations along an accurate geometrical and geographical depiction of the planned route. Therefore, in the early stages of any light rail transit project, track and traction power designers must interface to integrate the traction power system into the overall system design.

The final selection of substation sites is an iterative process with repeated simulations to confirm the capability of the traction power system to sustain peak-hour operations. The sequence of events to develop substation sites is as follows:

- The traction power designer, using the simulation program, selects theoretically ideal positions along the route, taking into account the distribution system's voltage drop and the lowest voltage acceptable to the vehicle without degrading performance. The normal, single contingency criteria for determining traction power requirements is to test the system with alternating substations out of operation.

- The designer discusses these proposed locations with the local power utility to determine any impacts of the proposed power demand on their network. The utility then evaluates the availability of power circuits and the potential impacts on its other customers.
- An agreement is eventually reached, if necessary, by moving the substation to enable it to be supplied from lightly loaded power circuits or by building spur cables to the substation location. It is also important, for reliability, that the power company avoid supplying two adjacent substations from the same circuit.

After an agreement is reached with the power company, the traction power designer can finalize the substation design. Newer substations for light rail systems are generally modular, factory assembled units, that are delivered to site complete. They are erected on a prepared base that incorporates an extensive grounding network below the concrete.

Substations are located along the track route as close to the wayside as possible within the constraints of available real estate. However, the final placement must also consider interfaces and underground cable duct routes for both the power distribution supply and return systems; access roadways; and security requirements. The impact of this construction on trackwork design is limited to the interfaces with the supply and return power distribution system.

Placement of a substation at, or near, a crossover is often desired to sectionalize electrical supply for each travel direction and to optimize the operational flexibility of the crossover.

11.3 WAYSIDE DISTRIBUTION

The trackwork element of the traction power supply system design should allow adequate space for the conduit to interface with the wayside distribution system. The electrical sectionalization of the distribution system usually takes place at the substation for all travel directions. Adequate space is required for conduit systems, including terminations, conduit risers, and manholes. Wayside distribution systems can be subdivided into the overhead contact wire system and supplemental cabling systems.

In systems utilizing overhead contact wire, wayside connections are made to the overhead catenary system (OCS) from trackside at substation supply points, switching station locations, crossovers, junctions, and wayside feed points. The connection of the power supply to the overhead suspension network impacts track design since the cables are routed in underground conduits and must include riser transitions at the appropriate height for termination. The riser transitions can be located at the sides of the OCS poles or within the poles, either of which requires an appreciable foundation at trackside. Once the power supply is terminated to the overhead wire, the power supply distribution usually remains on aerial structures and does not interface further with the track.

However, in visually sensitive areas where the community insists that only a single trolley wire be utilized, additional cabling is required to support electrical loading. This supplementary distribution is routed underground and conduit risers are required quite frequently (every third or fourth pole) to make the transition from the underground system to the overhead wire. This situation requires enlarged pole foundations, possibly stanchion foundations, for switches at each riser. At the power supply feed points to the overhead wire, it is common practice to utilize poles situated on the field side of the tracks instead of center poles to minimize impacts to the track design. This also limits the amount of underground conduit between and beneath the tracks.

The style of catenary and most of the basic design parameters can be developed prior to finalization of the track configuration. However the application of a catenary design to suit the track layout can only proceed after the track alignment has been finalized.

11.4 CATENARY ALTERNATIVES

There are generally three styles of catenary used on LRT systems: simple catenary, low-profile catenary and the traditional single trolley wire system. Simple and low-profile catenary systems may have fixed terminations that cause the conductors to rise and fall as the temperature varies or balanced weight tensioned to maintain constant tension and height under all weather conditions.

A simple catenary system uses a messenger wire to support the horizontal trolley wire. Both conductors are used to transmit power from the substation to the vehicle. The system height at the support—the distance between the contact or trolley wire and the messenger—is approximately 1.2 meters (4 feet). This allows spans between poles of up to 73 meters (240 feet).

The low-profile catenary system is similar to the simple catenary design, except that the system height at the support is reduced to approximately 457 millimeters (1.5 feet). This style is applied in aesthetically sensitive areas where a lower profile and simple single-wire cross spans are more desirable The trade-off, however, is that the span length between supporting poles is reduced to approximately 46 meters (150 feet).

The traditional single-wire systems are considered by some to be much less obtrusive in the urban environment. It provides power through a single trolley wire that must be supported at least every 30 meters (100 feet). The span length is limited by the sag of the unsupported trolley wire which, in high temperatures, could encroach on vehicular traffic as well as the ability of the supporting hardware to carry the weight of a whole span of wire. It also requires the wire to be supported electrically by parallel feeders that must be bonded frequently to the trolley wire to achieve adequate conductivity. These feeders may run underground through a series of ducts and manholes, which are expensive, or hung from poles, which are unsightly. This system, therefore, has twice the number of poles than the equivalent simple catenary system.

As mentioned above, modern, lightweight catenary systems adopt balance-weight tensioning to limit the load applied, therefore affecting the size of the poles, foundations, and hardware. However, this type of construction requires the system to be separated into 1-mile segments with weights applied at each end to maintain constant tension in the conductors. Therefore, the design requires overlaps to ensure smooth passage of the vehicle pantograph from one segment to the other.

11.5 CATENARY DESIGN

11.5.1 Introduction

Generally, technical papers have not addressed rail/catenary interface issues, since transit catenary design has developed from operating railway systems where the track is already in place and the catenary must allow for the existing layout. In many new transit systems, the track alignment has been selected prior to the catenary designer's involvement in the project. The results of this lack of coordination are chronicled in TCRP Report No. 7 *Reducing the Visual Impact of Overhead Contact Systems*. Involving the catenary designer in the track design/alignment selection process can be cost-effective and reduce the visual impact of the catenary system.

Horizontal and vertical track alignment, trackwork, passenger station locations, substation sites, etc., must all be determined before the preliminary catenary design can proceed. However, the locations and design of these components can greatly influence the catenary design and its visual impact on the environment.

11.5.2 Conceptual Stage

The catenary engineer's task is to develop a conductor configuration to supply power to the vehicle from a position over the track that will allow good current collection under all adverse weather, operating, and maintenance conditions. The engineer must develop the most economic solution, considering the aesthetic constraints set by the community. This task involves resolving the number of wires in the air with the number of poles, supports, and foundations to achieve an efficient and environmentally acceptable design.

The catenary system is the most conspicuous and possibly the most visually undesirable element of a light rail transit system. TCRP Report No. 7 discusses "visual pollution," to the extent that it cited a case where a community refused to introduce an electric-powered transit system because of the expected visual impact. Unfortunately wires are needed to distribute power to vehicles. Therefore, poles are needed to support and register them over the pantograph under all adverse conditions. However, if the track designer considers the catenary constraints, then the size and number of poles can be minimized.

The catenary distribution system interfaces with trackwork in the following manner:

- On single-wire catenary systems, the track designer must coordinate the longitudinal and transverse track feeder conduits that support the electrical distribution system.
- The track designer must also provide adequate clearance between tracks for foundations, poles, catenary balance weights, and down guys.
- Track design and maintenance standards must be coordinated so that the vehicle pantograph remains beneath the catenary wires under all adverse operating and climatic conditions.

11.5.3 Application of the Catenary System to the Track Layout

Since the wire runs in straight lines between support points and the track is curved, pole layout is a compromise between the number of poles and the requirement that the contact wire remain on the pantograph under all adverse climatic, operating, and maintenance conditions. Even though the pantograph is usually 1,980 millimeters (6.5 feet) wide, only

460 to 610 millimeters (18 to 24 inches) are available for the wire to sweep the pantograph head after allowing for track alignment, gauge, cross-level tolerances, vehicle displacement, roll, pantograph sway, and pole deflection. At the midpoint between supports, this distance is reduced to zero due to deflection of the wires under maximum wind and ice loading conditions.

The allocation of pole positions must take into account the limitations of the catenary style, the profile of the contact wire necessary to accommodate overhead bridges and grade crossings, track curvature, crossovers and turnouts, underground utilities, etc. Therefore, if the track is designed with the catenary constraints in mind, economies can be achieved. The following paragraphs identify parameters that should be considered by the track designer.

11.5.3.1 Track Centers

The clearance between poles and the track is defined by the system's dynamic clearance envelope, which comprises three elements: the vehicle dynamic envelope, construction and maintenance tolerances, and running clearances. Therefore, if center poles with supporting cantilevers on each side are desired to reduce cost and visual intrusion, then the distance between tracks should allow for this envelope from each track plus at least 305 millimeters (12 inches) to permit installation of standard-sized poles.

11.5.3.2 Horizontal Curves

If the track is tangent, there will be no track-related constraints, other than right-of-way boundaries, when placing the poles along track However, as the wire negotiates curves using a series of chords, the number of supports is very dependent on the curvature. Therefore, as with other light rail system components, avoidance of superfluous and extremely tight curves is most desirable in catenary system design.

11.5.3.3 Vertical Curves

Vertical curves become critical when in the vicinity of reduced-clearance overhead bridges. The rise and fall of the catenary messenger is governed by the formula:

$$\frac{WL^2}{2T}$$

where: W is the weight of the catenary
L is the distance between supports
T is the tension in the messenger

Therefore, if there is a change in vertical grade near an overhead bridge, as is required when track undercutting is programmed to achieve increased vertical clearance, then the catenary designer should consult with the track designer to ensure that the wire can negotiate the vertical curvature.

11.5.3.4 Interlockings

The catenary/pantograph interface is a dynamic system. There are certain constraints applied to ensure that the system operates efficiently under all speed and weather conditions. The pole positions at turnouts are tied to the point of intersection (PI). It is desirable for the distance between the inner crossover of a universal interlocking to be approximately the same length as the crossover (PI to PI).

Scissor crossovers can be wired; however they present many difficulties for the catenary designer. Usually, for maintenance purposes, the inbound and outbound tracks are separated into different electrical sections. With tracks crossing within 2 meters (6 feet), very limited space is available to insert an insulator and avoid the horns of the pantograph . This is particularly difficult in higher speed sections where constant tension catenary design has been adopted, since the movement of wires along track due to temperature change can aggravate the problem. Also since wires serving two separate crossovers in a universal interlocking is much less costly, scissor interlockings should be avoided when catenary is employed.

11.5.3.5 Track Adjacent to Stations

Architecturally the introduction of the catenary system is obtrusive. Architectural design tends to dictate the position of poles to suit the architectural theme within the station area. This impacts catenary pole positions adjacent to station area requiring close coordination between the architect, track and catenary designers to ensure adequate space for poles at stations and approaches.

11.6 TRACTION POWER RETURN SYSTEM

11.6.1 Territory with Two-Rail Track Circuits for Signaling

The traction power return system directly impacts track design. The traction power return system uses the running rails as an electrical conductor to "return" the traction power to the substation from which it was generated. Traction power supplied to the train enters the running rail through the vehicle wheels and is extracted from the rail through impedance bonds in cables installed at each substation. Therefore, track designers must allow for impedance bond installation, along with the associated conduit stub-ups and negative cabling, at each substation. Where there is more than one track, in addition to the impedance bonds at each substation, impedance cross bonds are also located along the track every 610 meters (2,000 feet) or less to equalize the traction return currents in the rails. At these locations, conduit stub-ups will be installed beneath the tracks connecting the two track directions. Impedance bonds are also required by the signal system at the end of each signal block.

11.6.2 Territory with Single-Rail Track Circuits for Signaling

Although most track circuits for signaling in new light rail systems are of the two-rail type, single-rail signaling track circuits do exist in older systems. In such systems, one rail is used for traction return and the other is designated the signal rail. This type of installation requires insulated joints separating the track circuits. With single-rail track circuits, the impedance bonds described in Section 11.6.1 are not required. The cross bonding provided between the traction return rails of separate tracks uses cables without impedance bonds for this purpose. Except for these differences, the same cabling is required between the traction return rail and substations as described in Section 11.6.1.

11.6.3 Territory Without Signaling Track Circuits

The requirements for traction return in this type of territory are similar to the those described in Section 11.6.1, except that no impedance bonds are required. Instead, cables are installed directly to the rails for both traction return at the substation and for cross bonding between the rails.

11.7 CORROSION CONTROL MEASURES

In designing dc traction power systems, it is common and desirable to isolate and insulate the running rails from ground as much as possible. These issues are discussed at length in Chapters 4 and 8.

The traction power return system interfaces with trackwork in the following manner:

- The siting of impedance bond positions and cross bonds to adjacent tracks must be coordinated.
- The selection of rail insulation for tie plates and fastening clips suitable for track and traction power requirements must be agreed to by all parties.
- Continuity bonds on jointed rails must also be coordinated.
- The track designer and construction inspector should ensure that ballast is clear of rails so that return currents do not stray into the ground and cause corrosion problems in underground pipes and cables.
- Special consideration must be taken when selecting the insulation of the rails at grade crossing and embedded track sections to ensure minimum leakage to ground.

11.8 MAINTENANCE FACILITY YARD AND SHOP BUILDING

The traction power return system in the maintenance facility yard and shop area is usually different from that adopted for the main line. The yard and shop area is usually designed and constructed along with the light rail system; therefore, adverse effects of stray currents can be allowed for in its design. Since the traction power return current can be more easily controlled in a yard by increasing the quantity and locations of return cables, the insulation system provided for the yard tracks may be somewhat less effective than the main line track system described herein. Yard tracks are most commonly placed directly on the ties without insulation. The grounding systems for the yard and main line must be electrically separate. This is achieved by inserting insulated rail joints in the yard entry track at each arrival and departure connection.

Yard track designers must still consider and account for the many conduit risers necessary to feed the numerous electrical sections in the overhead contact system. Extra coordination in yard areas should take place due to the additional users and electrical connections in the complex track layout.

In the maintenance facility building, the rails are installed directly into the shop floor system and are rigorously electrically grounded for safety of the personnel working on the vehicles. The return system is designed for current to return directly to the substation through cables to ensure there is no potential difference between the vehicle and the ground. Space for the conduit and cables connecting each track section to the building substation must be coordinated. The shop floor tracks also contain insulated joints that electrically separate these totally grounded tracks from the yard track system.

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Abbreviations used without definitions in TRB publications:

AASHO	American Association of State Highway Officials
AASHTO	American Association of State Highway and Transportation Officials
ASCE	American Society of Civil Engineers
ASME	American Society of Mechanical Engineers
ASTM	American Society for Testing and Materials
FAA	Federal Aviation Administration
FHWA	Federal Highway Administration
FRA	Federal Railroad Administration
FTA	Federal Transit Administration
IEEE	Institute of Electrical and Electronics Engineers
ITE	Institute of Transportation Engineers
NCHRP	National Cooperative Highway Research Program
NCTRP	National Cooperative Transit Research and Development Program
NHTSA	National Highway Traffic Safety Administration
SAE	Society of Automotive Engineers
TCRP	Transit Cooperative Research Program
TRB	Transportation Research Board
U.S.DOT	United States Department of Transportation